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Mankind, 11 (1977), pp. 2-10

1

Pleistocene Man in South Central Tasmania: Evidence from a Cave Site in the Florentine Valley

A. GOEDE and P. MURRAY*

Introduction

Geomorphological and palaeontological investigations in Beginners Luck Cave (146° 28′22″ E., 42° 34′21″ S.) during 1975 revealed at one site (site P) the presence of three stone artifacts and one probable bone artifact in a strongly cemented and deeply dissected late Pleistocene cave breccia. The deposit also contains some charcoal and abundant fossil bone material in a good state of preservation and has been dated. The bones represent two species of bird, six species of marsupials and two species of rodents. Many of the bones show signs of having been fractured and split and a few fragments have been charred.

Bowdler (1975) has recently obtained a date of 22,750 ± 420 years BP (ANU-1498) from an aboriginal occupation deposit at Cave Bay Cave on Hunter Island off the northwestern tip of Tasmania. Sigleo and Colhoun (1975) have from stratigraphical and geomorphological evidence deduced a Last Glacial age for a source-bordering sand sheet at Old Beach in South Eastern Tasmania which contained four artifacts but the deposit is lacking in datable material.

This paper discusses the geomorphological, stratigraphical and palaeontological evidence associated with the artifacts at the Beginners Luck Cave site and evaluates the archaeological and ecological significance of the find.

Geomorphology and stratigraphy

Beginners Luck Cave is located approximately 24 km N.N.W. of Maydena in a low limestone hill within the broad flat-floored valley of the Florentine River (FIG. 1). The cave entrance is situated nearly 3 km east of the river in dense, wet sclerophyll forest close to the outer margin of the valley floor and at an elevation of approximately 400 metres. To the east the country rises steeply to the summits of the Misery Plateau with elevations of over 1100 metres.

Streams on the plateau drain to the east and only short streams flow westwards down the escarpment with most of the water going underground on reaching the limestone. The valley floor is an area of low relief, in part covered with alluvial sediments, with low limestone hills from 10 to 20 metres high rising above its general level. Beginners Luck Cave is located in such a hill. It consists of a complex system of passages with varying dimensions and has four known entrances. Site P is located out of reach of daylight but close to entrance JF-81.

The passage containing site P rises in an easterly direction from one of the larger chambers in the cave. It had a former surface connection at its highest point which has become blocked by solifluction material. FIG. 2 represents a longitudinal section of the passage with its outline indicated by heavy lines. Projected on it is a section of the north-facing wall. The section is dominated by two lithostratigraphic units.

The lower unit consists of mixed fluvial gravels and is widespread throughout the cave, the maximum thickness exposed in section being 1.7 metres though nearby exposures indicate a maximum depth of at least 5 metres. A sediment sample was taken approximately 0.5 metres east of the line of cross-section (FIG. 2). Analysis of this sample showed that it contained pebbles of

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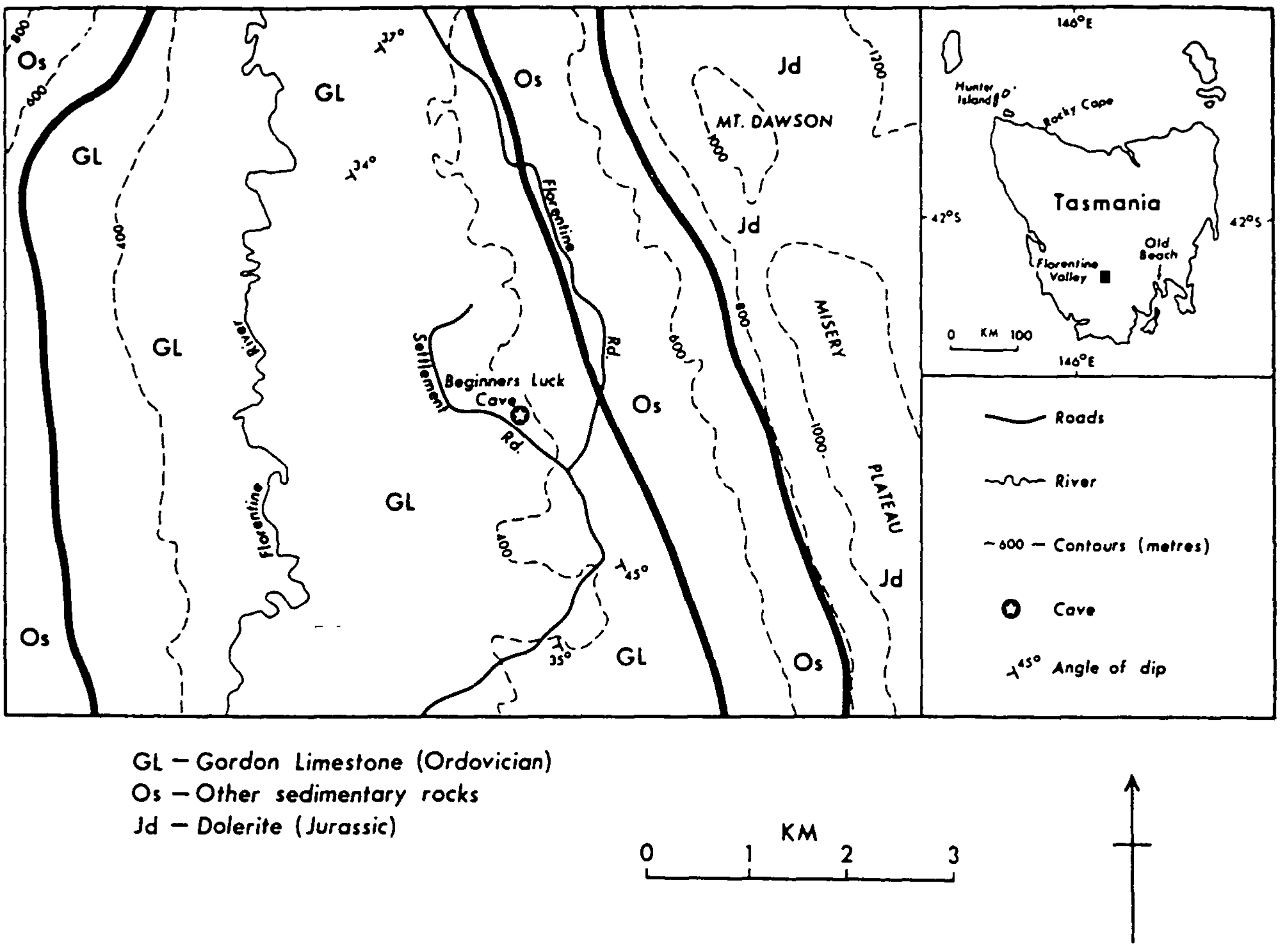

FIG. 1 Locality and lithological map of part of the Florentine Valley (lithology after Corbett, 1963).

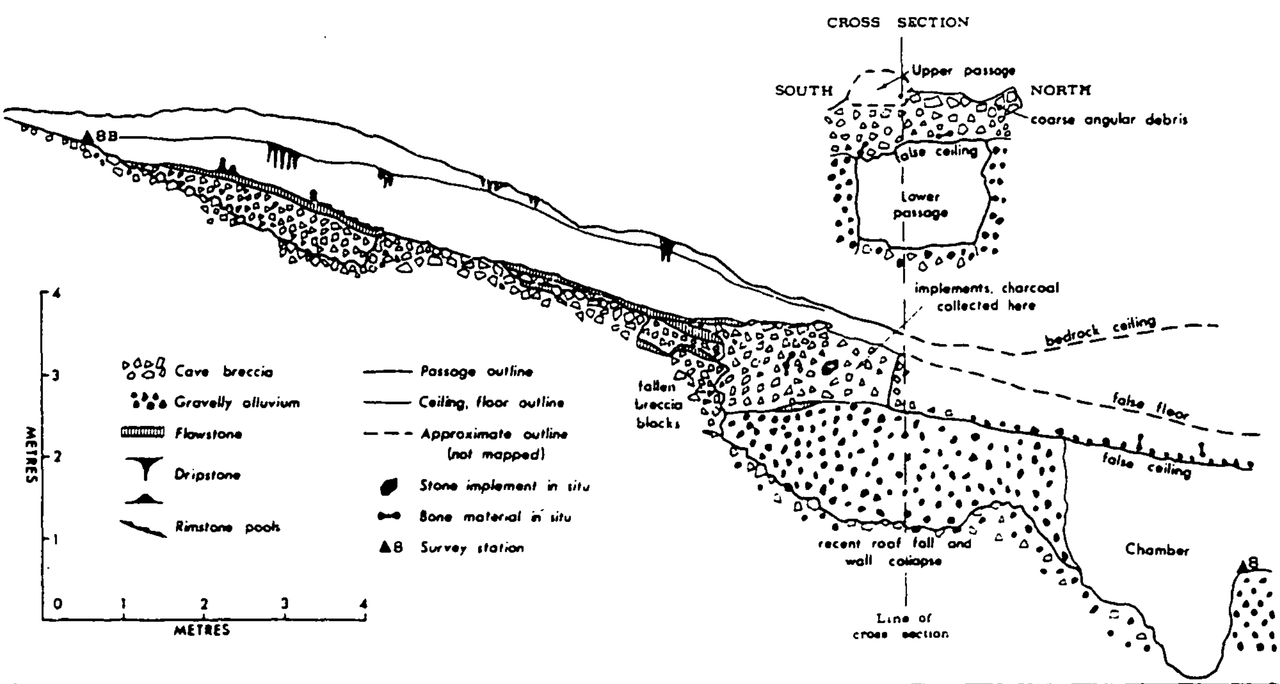

FIG. 2 Longitudinal and cross sections of 'site P' passage—Beginners Luck Cave (JF-79).

dolerite (63.9%), mudstone (29.2%), sandstone (5.4%) and quartzite (1.5%), none of which derive from the cave or its immediate vicinity (FIG. 1). Weathering of the pebbles is uniform and indicates that it occurred after deposition. This lack of pre-depositional weathering, the faceted nature of the dolerite pebbles and the low degree of rounding suggest that they were derived under conditions of physical weathering (?frost) and transported to the floor of the valley by short, high-energy streams. Similar deposits occur extensively on the surface underlying the valley floor between residual hills. Exposure is poor but one bulldozer scrape close to the cave revealed 1.8 metres of alluvial sediment. Its nature, size range and weathering characteristics are very similar to the alluvial cave fill.

In the cave the alluvial unit is overlain with slight erosional disconformity by a limestone breccia representing a typical entrance facies deposit which reached its present position as a debris flow. The breccia consists of angular limestone fragments in a sparse matrix of dull brown (7.5 YR/5/4) clay (Standard Soil Color Chart, 1965) with a pH of 8.5. Near its base at site P, the deposit contains numerous small fragments of limestone down to 2 mm with occasional fragments up to 100 mm long. The nature of the fragments strongly suggests production by frost weathering. Bones of the broad-toothed rat *Mastacomys fuscus* are particularly abundant here. Upwards the limestone fragments become coarser and a substantial accumulation of large fragments (up to 40 cm long) occurs locally. Accumulation of such blocks is particularly marked where the upper boundary of the deposit meets a low point on the cave roof (FIG. 2, cross-section).

A sediment sample was taken close to this point and found to contain 106 rock fragments. Two of these were found to be stone artifacts—one made of fine-grained hornfels and the other of a coarse-grained, dark-coloured quartzite. The remaining fragments were all limestone. Size characteristics (long axis) were: mean 36.5 mm, median 34.7 mm, bimodal with modes at 24.9 and 43.8 mm. Only 16 fragments showed a slight degree of rounding.

At the cross-section the thickness of the deposits is only 75 cm but increases rapidly upslope. Subsequent to sampling a third stone artifact was found *in situ* (FIG. 2) and has been left in position 40 cm from the base of the deposit and 50 cm from the top. Much of the sediment is strongly cemented by post-depositional impregnation with calcium carbonate in strong contrast to the lower alluvial unit. In places the upper surface of the deposit is covered with sheets of flowstone with rimpools and stalagmites. Because of its strongly cemented nature the breccia has resisted subsequent erosion and in the lower part of the section has been left as a false ceiling and floor, completely subdividing the passage into two levels. The deposit contains abundant bone material belonging to a variety of species. A few of the bones have been burnt. Scattered fragments of charcoal are common throughout.

The breccia is considered to be a solifluction deposit which entered the cave through a former entrance upslope from the survey station 8B (FIG. 2). The entrance became blocked during the final phase of clastic deposition. Some of the large blocks were probably derived from the ceiling but the bulk of the material appears to have come from the former entrance. The nature of the deposit suggests that frost weathering played an important part in the production of the coarse fraction which became mixed with archaeological material and pre-existing residual soil. It was then transported downslope by solifluction processes and redeposited. Its lithological composition indicates that it is entirely of local origin in marked contrast to the underlying alluvial sediments. Locally there has been some erosion of alluvial material and mixing with the overlying breccia. The slight rounding of some of the limestone fragments reflects abrasion due to transport rather than being the result of solution processes.

In one place some flowstone occurs between the two units but this material could be younger than the breccia as it may have been deposited in a void created by differential compaction of the two sedimentary units.

After clastic sedimentation ceased, chemical deposition of calcium carbonate became dominant. Cementing of the breccia took place before significant erosion of the cave fill occurred. There is a strong indication that sediment removal took place in two stages separated by a period of carbonate deposition, which has been preserved on a prominent bench at approximately the level of station 8 (FIG. 2). At present both erosion of clastic sediments and deposition of calcium carbonate are active processes.

Palaeontological content

The alluvial unit contains little if any bone material at site P although bones are known to occur near the top of the unit at a nearby site.

The breccia is quite rich in bone material which occurs throughout but the broad-toothed rat (*Mastacomys fuscus*) appears to be most abundant near the base and large macropods in the upper part. The bones show a slight erosional gloss indicating some abrasion during transport. In addition to the bones the tiny planispiral shell (1.5 mm diam.) of a land snail was found. Identification of the bone content is:

Native cat (*Dasyurus viverrinus*): 1 left ramus

Tiger cat (*Dasyurus maculatus*): 1 canine tooth

Barred bandicoot (*Perameles gunnii*): 1 left ramus

Tasmanian pademelon (*Thylogale billardieri*): 1 humerus, 1 fibula

Brush wallaby (*Macropus rufogriseus*): 8 femora, 7 tibiae, 1 ilium, 1 maxilla, 10 vertebrae, 2 humeri, 1 calcaneus, 2 mandibulae, 2 metatarsi IV, 2 fibulae (one a presumed artifact), 3 phalanges.

Undetermined macropodid: 1 metatarsus IV, 1 clavicle, 1 scapula

Common wombat (*Vombatus ursinus*): 1 ulna, 1 maxilla

Broad-toothed rat (*Mastacomys fuscus*): 20 maxillae and mandibulae (minimum of six individuals), 5 tibiae, 2 humeri, 5 femora, 3 innominates.

Long-tailed rat (*Pseudomys higginsi*): 1 mandible

Indeterminate mammal material: 2 ulnae, 20 ribs, 1 ilium, 1 fibula, more than 20 fragments including 2 charred pieces.

In addition some bird bones were also collected and sent to J. van Tets (CSIRO Division of Wildlife Research) for identification). Van Tets (in press) has identified the material as belonging to Tasmanian Native Hen (*Tribonyx mortierii*) and Sooty Shearwater (*Puffinus griseus*), the latter being represented by a left femur lacking the distal end and a left tarsometatarsus with damaged ends.

Much more material remains in the deposit but excavation ceased when the archaeological nature of the site was recognized.

Evidence of human association

The condition of the fossil material contained in the breccia at site P strongly suggests that at least some, if not most of these bones represent food remains brought into the proximity of the cave entrance by humans. It would be difficult to imply human economy for these remains if certain specific indications were absent. Caves frequently contain skeletal remains of animals that have either fallen into shafts or were brought in by scavengers. A variety of physical agencies can also be responsible for similar accumulations. However the remains are distinctly marked by human activity. The evidence includes charred bone fragments, butcher marks, spiral fracturing of long bones, splitting of dense bones such as calcanei and the probable modification of a wallaby fibula (*Macropus* sp.) for use as an implement. A peculiarly modified *Macropus* (probably *rufogriseus*) tibia is also present.

Charred bone fragments are not abundant in the sample, but they clearly indicate that some of the remains were subjected to open flames or extremely hot coals. They are identical to the ubiquitous charred food remains found in other archaeological contexts. The suggested bone artifact is described with the stone tools elsewhere in the paper. The remaining four items of archaeological interest are described as follows:

Butcher-marked bone: Nicks and incisions believed to be butcher marks are present on the lateral side of the distal end of a left *Macropus* (probably *rufogriseus*) femur. Four distinct striations lie perpendicular to the long axis of the bone. Microscopic examination of the marks suggests the use of a stone tool. The fragment itself is spirally fractured.

Spiral fracturing and split bones: Many of the recovered long bones are broken. The breaks have produced highly irregular edges characteristic of fresh bone. Dried bone, particularly in a carbonate environment, becomes brittle and tends to produce clean, even surfaces when broken, or alternatively, tends to shatter. Nearly all of the breaks in the Florentine material suggest that there was considerable collagen present in the bone when the damage occurred. The fragments are also relatively large in contrast to the small comminuted bone fragments often associated with Tasmanian devils (Douglas, Kendrick and Merrilees, 1966). Spirally fractured longbones are characteristic of human food remains and rarely occur in other contexts. It is probable that these bones were broken with hammerstones or by smashing against rocks. The fracturing of calcanei and other extremely compact bone is also suggestive of human activity. It is possible that these bones were broken to obtain marrow, the usual purpose attributed to bone breaking activity in archaeological contexts.

Incised tibia: This possible artifact is the right tibia of an immature *Macropus*, probably *rufogriseus*. The specimen was entirely coated with a thin layer of flowstone when recovered. More than fifty shallow scratches were found on both the lateral and medial sides. These incisions run perpendicular to the long axis of the bone, and appear to start from either direction. There are similar cuts along the tibial crest as well. The marks repeat a narrow and somewhat broader pair of lines for each incision. While unstandardized looking, they are neither rodent tooth marks or the result of fungal attack; nor does the repetition of the same marks and the alternation of their source support the hypothesis that the scratches are the result of the bone having coursed over sharp materials (such as limestone fragments). Other bones recovered from the same area and in similar condition, including some coated with flowstone, are free of obvious marks or scratches. It is tentatively suggested that the marks are the results of human activity.

The artifacts

This section describes the two stone artifacts removed from the cave site and also a probable bone artifact.

1. A dark-coloured quartzite flake struck from a cobble with a 2 mm thick weathering rind (FIG. 3A):

This specimen is roughly trapezoidal in

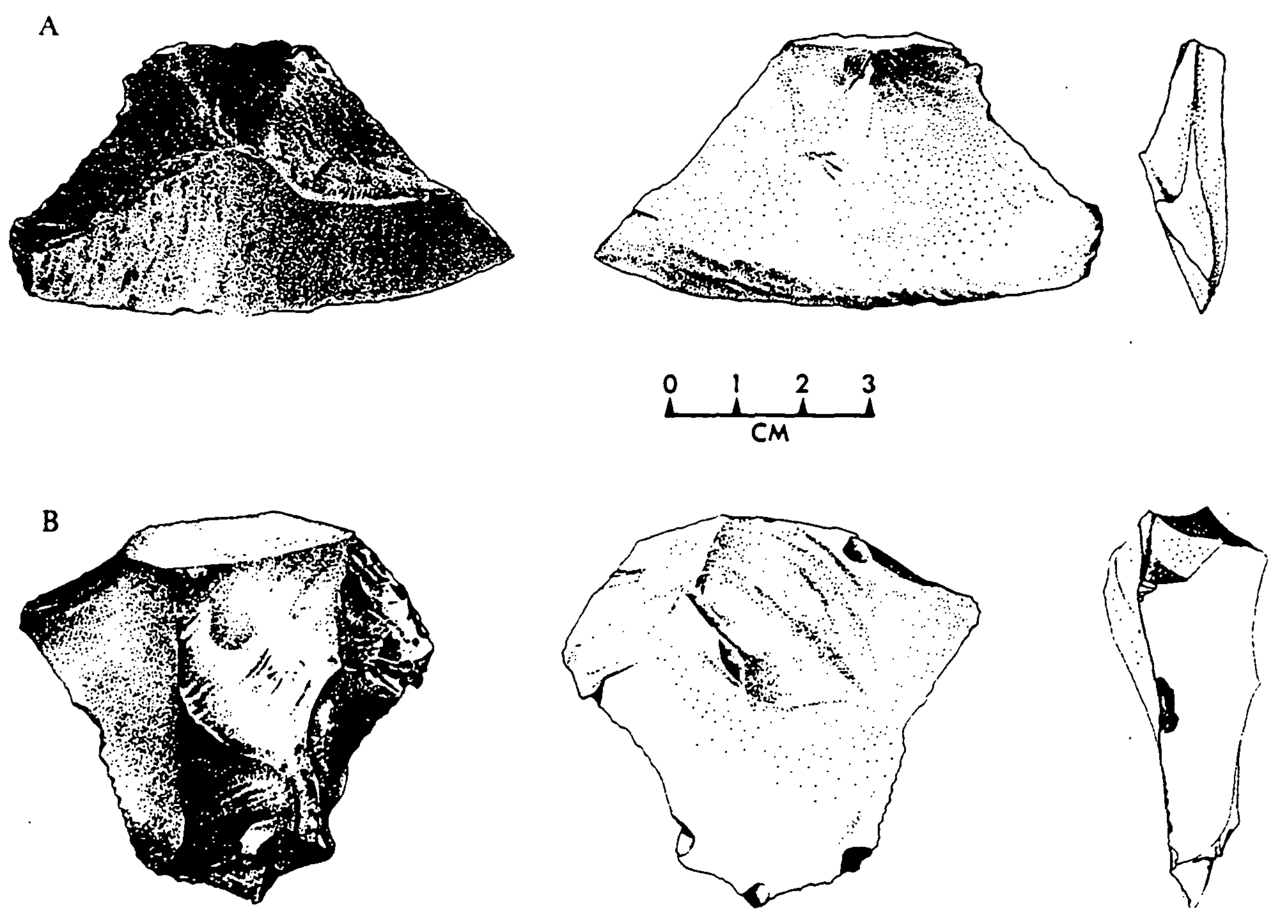

FIG. 3 Two stone artifacts from site P. Beginners Luck Cave.

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outline, increasing in width distally. A striking platform is present. There is a well-developed bulb of percussion and bulbar scar. Two large flake scars on the dorsal surface were removed from the cobble before the flake was detached. The bulbar surface is unweathered and free of matrix. The distal edge of the flake presents a convex, relatively blunt potential working surface. A portion of this edge appears to have been steepened by the removal of six or seven small, short flakes. A concave, ascending side presents a sharp, unretouched edge. Dimensions: maximum length 77.5 mm, maximum width 40.2 mm, maximum thickness 11.1 mm.

2. Flake struck from a grey hornfels nodule (FIG. 3B):

This is a thick, trapezoidal flake, narrowing and thinning out distally. There is a broad striking platform, prominent bulb of percussion and bulbar scar. The flake was struck from a core bearing large flake scars. Hinge fractures on the dorsal side near the proximal end suggest several thinning blows were made before the flake was detached. There are four prominent spurs extending from the perimeter of the flake. The presence of small flake scars on the most prominent spur attests to the use of this projection. A long, steeply bevelled edge running parallel to the axis of the flake has been provided with a small notch 8 mm long by 2 mm wide. Use-chattering also occurs along the length of the edge. Notched and spurred flakes are typical of Tasmanian stone tool assemblages (Jones, 1971:425). Dimensions: length 63.2 mm, width 60.0 mm, thickness 20.5 mm.

3. Spatulate bone implement from the left fibula of a small macropodid:

The proximal end of this implement appears to have been broken. Examination of the surface of the specimen with a binocular microscope demonstrated an increase in the density of nicks and fine striations towards the distal end. The distal end of the artifact was produced by flaking. Recognizable secondary shaping by abrasions appears to be lacking. The contours of the individual breaks or 'flakes' (of which there are a minimum of five) have probably been rounded by use. Wallaby fibula 'spatulas' have been previously recorded from sites in Tasmania (Jones, 1971). Their function is unknown. Dimensions: maximum length 94.5 mm, maximum width 9.0 mm, maximum thickness 4.0 mm.

Dating

Material obtained for dating at site P consisted of scattered fragments of charcoal obtained from the limestone breccia in approximately the same stratigraphic position as the stone artifacts (FIG. 2). A radiocarbon date was obtained of 12,600 ± 200 yrs BP (R5001/4) (McGill, pers. comm.). The sample was submitted with a request to remove any calcium carbonate before dating. However, perhaps because of the small amount involved (5.25 grams), this was not done and the date thus represents a minimum age.

Another date of significance was obtained by dating bone belonging to an extinct browsing Kangaroo (*Sthenurus occidentalis*) from site M in another part of the same cave. The site has not been discussed but consists of a scatter of bones on the surface of a muddy slope. There is no clear evidence of association with human activity. A radiocarbon date on the organic carbon residue of the bone yielded an age of 14,450 ± 250 yrs BP (R5001/3) (McGill, pers. comm.). Any C14 date on bone should be treated with caution as such material is readily contaminated by younger organic acids contained in seepage water at any time since its deposition. The fact that the bone was never buried by subsequent sedimentation is likely to have minimized the risk in this case.

Discussion

A possible evolutionary sequence of cave development and phases of clastic and chemical deposition is shown in FIG. 4. The alluvial cave fill is considered to represent aggradation by a vadose stream which derived its material from the Misery Plateau escarpment to the east (FIG. 1). The nature of the deposit indicates significant mechanical (?frost) weathering and rapid transport and deposition (FIG. 4B). Chemical weathering is post-depositional and remarkably uniform in character. The degree of weathering of the dolerite pebbles suggests that the deposit is unlikely to predate the Last Glacial Stage (75,000-10,000 BP) but that deposition probably occurred early during that stage. Deposition may have ceased as a result of a change in climate but more likely because

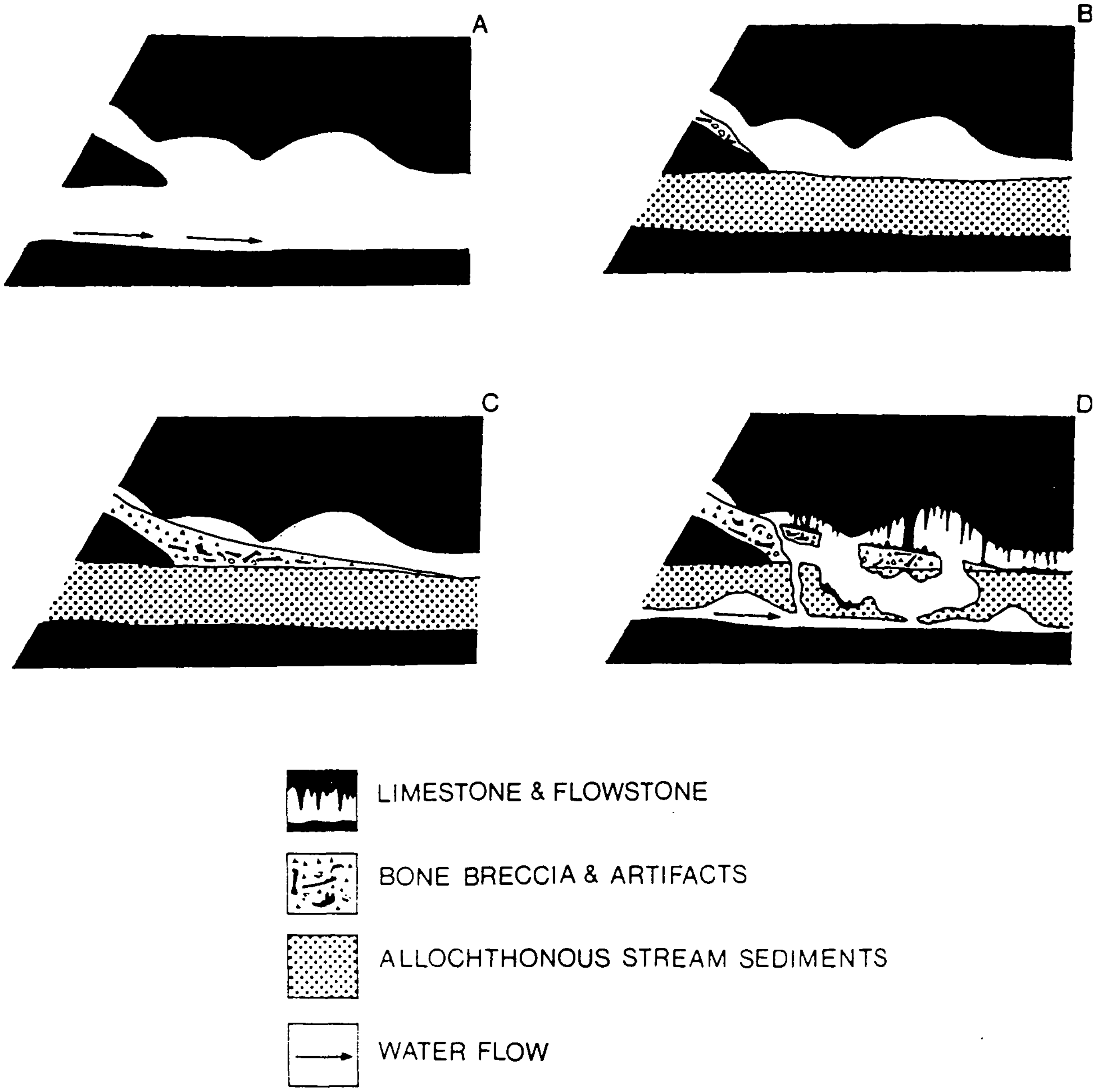

FIG. 4 Evolutionary sequence of cave development and depositional phases.

of diversion of drainage to surface routes as underground channels became blocked with sediment.

At a later time, dated at 12,600 ± 200 yrs BP, a former cave mouth was occupied by humans who left behind implements, bones and charcoal as evidence. In FIG. 4B this occupation is shown as having occurred *prior* to the onset of conditions causing the production of frost-weathered limestone debris at the cave mouth. This became mixed with archaeological material and pre-existing chemically weathered residues (clays) and was introduced into the cave as a solifluction deposit (FIG. 4C). Mass movement continued until the entrance was blocked off.

Previous evidence of late Last Glacial periglacial activity in the Florentine Valley has been reported by Davies (1974). Charcoal in the A horizon of a convoluted podsolized soil at about 500 metres gave a radiocarbon date of 14,200 ± 700 yrs BP (GaK 486). This soil was overlain by a layer of solifluction material suggesting periglacial activity after that date.

In view of the very late Last Glacial date obtained at site P, the possibility must be considered that human occupation was *contemporaneous* with the accumulation of the limestone breccia. It may be that the site was occupied sporadically during the summer when conditions were favourable while periglacial processes were active during the winter months.

During the Holocene (10,000-0 BP) there has been no significant clastic deposition but at least two phases of erosion took place, the second still active today (FIG. 4D). Deposition of calcium carbonate has probably been continuous during the Holocene. Significant deposition must have taken place *before* the first phase of erosion in order to cement the cave breccia to such an extent that much of it was able to remain as a false floor and ceiling.

The Pleistocene occupation of Tasmania has already been firmly established by Bowdler (1974a, 1974b, 1975) at the Cave Bay site on Hunter Island, while Sigleo and Colhoun (1975) have shown that humans were probably present in the lower Derwent Valley between about 20,000 and 10,000 years ago.

Of particular interest at the Beginners Luck Cave site is the presence of bones belonging to the Sooty Shearwater (*P. griseus*). Van Tets (in press) states that:

> It is possible that the Sooty Shearwater was blown inland by a gale and its remains either washed into the cave or carried there by a predator. It is more likely, however, that it was picked up on the coast and carried to the cave by man as an ornament or as food.

Most of the significance of the cave site in the Florentine Valley lies in the fact that it demonstrates at least sporadic occupation of a truly inland site at an elevation of some 400 metres at a time when the climate must have been much more severe than at present. The occurrence of solifluction deposits, and the faunal composition indicated by the bone content of the breccia at site P, indicate a much more open environment than the present-day, dense, wet sclerophyll forest.

It has generally been held that 'in late-glacial times, most of Tasmania was inhospitable and probably uninhabited' (Jones, 1968:200). Recent pollen work (Macphail, 1975) has indicated however that prior to 11,500 C14 years BP plant communities 'in Western Tasmania were either grasslands or palynologically unrecorded formations such as sclerophyll heath and sedgelands' while communites 'on Tasmanian mountains . . . were mainly herbaceous'.

It now seems likely that, during spells of relatively settled summer weather, the valleys of southwestern Tasmania would have been much more readily accessible to humans in late Last Glacial times than they are today because of the open nature of the vegetation. Such valleys may also have possessed a richer and more varied fauna including the larger browsers and grazers—especially in edaphically favourable areas such as the Florentine Valley.

Also of significance is the comparatively young date (14,450 ± 250 BP) obtained at site M on bone material belonging to *Sthenurus occidentalis*. It suggests the late survival of elements of the Pleistocene megafauna in Tasmania and the possibility that they co-existed with man. Late survival of such elements is also supported by evidence from cave bone deposits at Montagu in northwestern Tasmania (Murray and Goede, in press). More extensive excavation at site P may yield remains of extinct fauna. Pleistocene bone deposits recently discovered in two other caves in the Florentine Valley and containing extinct species will yield further information on the late Pleistocene fauna of the area and perhaps also on the presence of humans.

Discovery of site P suggests the probability that other archaeological sites may be found in limestone caves in the high rainfall areas of western Tasmania, even though these high-rainfall areas of the interior southwest do not seem to have been occupied and exploited in the ethnographic present (Jones, 1968:200).

Acknowledgements. We thank the University of Tasmania for financial support towards the field investigations and radiocarbon dating for this paper. We are grateful to members of the Tasmanian Caverneering Club, who explored the system and drew our attention to the presence of bone deposits, and particularly to Therese Goede who discovered site P.

We acknowledge the assistance of Denis Charlesworth in carrying out laboratory analysis of sediments and preparation of bone material and of Mr Guus van de Geer and Mrs Kate Morris in drawing FIGS 1 and 2.

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PLEISTOCENE VERTEBRATE REMAINS FROM A CAVE NEAR MONTAGU, N.W. TASMANIA

by

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RECORDS OF THE

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PLEISTOCENE VERTEBRATE REMAINS FROM A CAVE NEAR MONTAGU, N.W. TASMANIA

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ABSTRACT

The results are presented of a study of vertebrate remains and associated sediments found in a small, recently discovered dolomite cave (MU-206) in north-western Tasmania. A list of species identified to date is presented and the geochronological and palaeoecological significance of the fossils is indicated.

A description is given of the evolutionary history of the cave and the character of the cave deposits is examined. This is supplemented by an assessment of the condition, completeness and relative position of the fossil material from the site.

PHYSICAL SETTING

Tasmania is a mountainous island with numerous small areas of karst, located predominantly in the high rainfall zone of the western half of the state.

The Montagu karst consists of two small Upper Precambrian dolomite hills rising to a maximum height of six metres above a marshy plain near the Montagu River (figure 1). It is located in the centre of an extensive coastal plain with the land sloping gently northwards towards Bass Strait. Local drainage also trends in this direction.

The area has an extensive veneer of Pleistocene and Holocene sediments ranging from shallow marine and estuarine deposits to aeolian, alluvial and paludal sediments. The Pleistocene cover is interrupted by ridges and isolated outcrops of basement rocks which are predominantly Upper Precambrian and Cambrian in age. A description of the regional geology is given by Gulline (1959). The Precambrian outcrops consist of quartzites, conglomerates and dolomites (Smithton Dolomite) and are widespread. Cambrian rocks include siltstones, tuffs, greywackes, breccias and conglomerates as well as some basic volcanic rocks.

Marine and freshwater Tertiary sediments, including limestones, are of limited extent. They are generally flat-lying in contrast to the strongly folded Precambrian and Cambrian rocks. Outcrops of Tertiary basalts occur locally but are extensive only in the south-east corner of the area shown in figure 1.

Pleistocene high sealevels are indicated by the presence of raised shorelines associated with shallow marine deposits and relict coastal dunes. Further east, three raised shorelines described by Chick (1971) are suggested to be of Last Interglacial age. The highest stands at approximately 20 metres above higher high water mark. Regression of the Pleistocene sea from maximum levels is indicated by extensive series of beach ridges. Some of the older series have been almost completely buried by subsequent peat accumulation.

Artesian springs occur locally in association with deposits of peat and freshwater algal marl. Those near Mella (Mowbray Swamp) are associated with well developed spring mounds. Both the Mowbray and Pulbeena springs are characterized by a very high carbonate content (400 p.p.m. at Mella and 750 p.p.m. at Pulbeena) indicating the presence of dolomite below the Pleistocene sediment cover. Pleistocene vertebrate remains have been recovered from both sites (Gill and Banks, 1956; Hope, 1973; Banks, Colhoun and van de Geer, 1976). Remains have also been recorded from a small dolomite cave (Scotchtown Cave) discovered near Smithton during mining operations in 1942.

The Montagu area is located approximately 41° South and 140° East. It is characterized by a mean annual temperature of approximately 13°C. The mean temperature of the warmest month (February) is close to 17°C while the mean temperature of the coldest month (July) is just above 9°C. The mean annual precipitation is 115 cm with a winter maximum. Not less than 35% of the annual precipitation falls in the three winter months (June-August) but only 15% during the three summer months (January-March).

The Montagu karst is within a wet sclerophyll forest giving way to swamp associations in poorly-drained portions of the surrounding plain. Three caves are known in the area. All contain deposits which include vertebrate remains. Main Cave (MU-201) and Pleisto Scene Cave (MU-206) are located on the western side of the Grunter Road, while the third, an unnamed cave (MU-205) is found in a dolomite outcrop on the opposite side of the road. The direction of dip of the dolomite is SW with the angle of dip varying from 35° to 58°. All the known cave entrances are located on the anti-dip side of the hills where they rise steeply from the surrounding country to form low cliff faces up to 5 metres high. The opposite south-east facing slopes merge gradually into the plain.

CAVE EVOLUTION

The caves have developed under varying groundwater levels which are probably related to past changes in sealevel as the location of the area is marginal to the estuarine plains of the Montagu River. An early stage of shallow phreatic development, related to a high groundwater level, is suggested by arched and flat roofs except where locally modified by rockfall. This appears to have been followed by a period of downcutting under vadose conditions associated with a falling water table. Much of the evidence for this phase is obscured by subsequent intermittent deposition of locally fossiliferous clastic sediments which can be subdivided into three stratigraphic units. This indicates a third phase of cave evolution at a time when groundwater levels were low. The sediments vary from mass-movement deposits containing abundant angular dolomite fragments to clay-rich water laid sediments accumulated under very low energy flow conditions in ponds and underground channels.

A subsequent period of marked but localized flowstone deposition has cemented the surface layers of the underlying clastic sediments in places. This was followed by a period of erosion which dissected some of the cave fill and undermined flowstone-cemented floors to produce "false floors" and protruding ledges. The final episode, which apparently still continues, is another period of localized flowstone deposition.

DESCRIPTION OF CAVE

The entrance is located in a jumble of rocks on a steeply rising north-facing hill slope. It measures approximately 80 cms across and has a roughly triangular shape. A 2.5 metre drop leads to a fissure about one metre wide and four metres long trending in a southerly direction. The floor consists of brown mud with some decaying wood and leaves (figure 2). A small, steeply sloping hole leads downwards about 1.5 metres, from almost directly below the entrance, to a horizontal passage. This passage shows evidence of having been almost filled with strongly-cemented, bone-bearing dolomitic breccia, remnants of which can be seen adhering to the eastern wall.

From the passage a horizontal slit 40 cms high leads to a small chamber (Chamber A) with horizontal dimensions of three by six metres and a maximum height of three metres. The chamber is located immediately below the entrance fissure and separated from it by a "false ceiling" consisting of a double layer of cemented bone-bearing breccia.

On the western side of the chamber, towards the northern end, a 1.5 metre high section of clay-rich alluvial sediments is exposed. The eastern wall appears to be composed mostly of bedrock with some flowstone. From its base extends a six metre long easterly trending passage which contains standing water in winter. It has a clay floor and a bedrock roof containing many actively growing stalactites.

From Chamber A the passage continues to a flowstone bridge. The flowstone sheet was originally formed on the upper surface of the fill sequence as indicated by the adherence underneath of fragments of strongly cemented cave sediment. Dissection of the clastic deposits after deposition of the flowstone has left it suspended above the floor of the present day passage.

At this point a north-south trending passage is entered. It is characterized by smoothly rounded ceilings and has an average height of 1.5 metres. Chamber B is located a short distance along the passage in a southerly direction. Bone-bearing dolomitic breccia is exposed both in the ceiling and the floor. The area of exposure in the ceiling is 0.5 by 2 metres and is contained within a fissure sloping upwards at an angle of approximately 50^{o}. The floor exposures consist of a dissected debris cone extensively covered with flowstone and located on the western side of the passage. At its outer margin it grades at a low angle into the upper surface of the cave fill sequence. This surface has also been dissected and is best preserved as a narrow bench on the eastern side of the passage.

The cave continues for a short distance beyond Chamber B as indicated in figure 2. Bone breccia also occurs near the furthest point reached as shown in section AA' (figure 2) but this site has not yet been excavated or sampled.

NATURE AND STRATIGRAPHY OF CLASTIC SEDIMENTS

A stratigraphic sequence of the deposits is best seen in Chamber A although the base is not exposed (figure 3). Three sedimentary units can be identified. Lowest in the sequence are 1.5 metres of clay rich, fine-grained alluvial sediments (Bed 1) seen in section on the western side of the chamber. At the base the deposits are reddish brown (5YR/4/8) grading upwards into yellowish brown sediments (10YR/5/6) which make up the bulk of the deposit (Japanese Revised Standard Soil Color Charts). The top 40 cms are dark reddish brown (5YR/3/4) and appear to represent a fossil soil (Bed 1 soil). This material is rich in colloidal organic matter but an attempt at pollen extraction was not successful. It also contains sporadic angular dolomite fragments. Small fragments of bone are dispersed throughout but are poorly preserved. The pH varies from 8.5 to 9.0.

The sediments just described are overlain by a dolomite breccia up to 50 cms thick (Bed 2) with a sharp depositional contact. Bed 2 is strongly cemented and forms a projecting shelf making up part of the roof. As well as bones, it contains numerous angular dolomite fragments down to only a few millimetres across. Most of the material has a sparse matrix of fine-grained sediment but locally an open framework occurs. The nature of the material suggests strong physical weathering, probably by frost.

The highest part of the roof exposes the base of the upper unit (Bed 3), which is also a dolomite breccia. Its thickness cannot be measured directly but must be less than one metre. It is also strongly cemented and contains abundant fossil vertebrate remains. The sub-angular dolomite fragments it contains are coarser than in the underlying layer and generally range from 1 to 10 cms in diameter with a few large blocks of up to 40 cms. It also contains a much more abundant matrix of fine-grained sediment. The nature of the dolomite fragments again indicates derivation by physical weathering but under less extreme conditions.

Most of the excavations have taken place in Chamber B where the stratigraphy is less clearly exposed. At an early stage of the excavations material excavated from the roof was kept separate from that excavated from the floor and debris cone. On analysis of the material it became apparent that both contained the same fauna and that the deposits were of the same nature. In subsequent excavations specimens from the two sites were combined.

The sediments excavated from both roof and floor sites in Chamber B are very similar in nature to Bed 3 in Chamber A and occur in the same stratigraphic position. Henceforth they will be referred to as Bed 3B. However, a few scattered, water-rounded quartz pebbles were found as well as one water-rounded quartz crystal and a number of strongly lateritized non-carbonate sedimentary rock fragments. One of the fragments contained a fossil pectinid *Mesopeplum antecedens* (Singleton) - a Tertiary marine fossil reasonably common in the Janjukian and Longfordian (Darragh, T. A., pers. comm.). It has probably been derived from a Tertiary cover rock which has since been eroded. The sediments are mostly bright brown (7.5YR/5/6) and have a pH of ·9. Bed 2 does not seem to be represented in Chamber B where Bed 3B rests directly on a lower unit of fine-grained alluvial sediments containing some poorly preserved bone material (Bed 1B).

Beds 2 and 3 represent typical entrance facies deposits which were derived from surface openings under conditions favouring mechanical weathering and mass movement and were transported by solifluction processes to be deposited as sloping sheets and debris fans. The absence of Bed 2 in Chamber B suggests that the surface opening which would have allowed its accumulation was not yet in existence at the time of its accumulation in Chamber A.

DISCUSSION

Bed 1 appears to represent aggradation by a slow-moving vadose stream. It may mark the onset of cold conditions early in the Last Glaciation resulting in soil instability and consequently an increase in sediment load. When accumulation ceased it appears to have been followed by a period of stability perhaps reflecting a return to milder climatic conditions. This is indicated by the fossil soil developed on Bed 1 in Chamber A. Some bones appear to have accumulated on this surface. Two upper incisors probably belonging to *Palorchestes* sp.[1] fall into this category.

Bed 2 is a dolomite breccia representing an entrance facies deposit. The abundance of small angular fragments of dolomite and the occurrence of open framework material indicate strong frost weathering. The sediment has all the characteristics of a solifluction deposit and suggests accumulation under surface conditions with an open and discontinuous vegetation cover, at least at the dolomite outcrops.

It has been observed that dolomites of similar age, cropping out further south (42° 57′ S) and in a more continental situation near Mount Anne at altitudes of up to 1000 metres, are not at present subject to active frost weathering in winter. Therefore, frost weathering at the Montagu cave site would seem to require a lowering of winter temperatures equivalent to an altitudinal lowering of winter temperature zones of not less than 1200 metres. This corresponds to a reduction in the mean winter temperature of 8°C (Haltiner and Martin, 1957). It suggests that Bed 2 accumulated under conditions approaching maximum cold during the Last Glaciation.

Bed 3 is similar in origin to the middle unit but appears to have accumulated under less extreme cold climate conditions. The dolomite fragments are larger and there is a much greater abundance of fine-grained matrix. In both Chambers A and B this sediment is rich in fossil bone material and the fossil bone material excavated in Chamber B comes from this bed.

EXCAVATION METHODS

Chamber B locality of Pleisto Scene Cave has been extensively sampled. Small samples have been obtained from Chamber A in the same cave, and from one of

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1 Positive identification of *Palorchestes* from Chamber A is based on a lower incisor.

several deposits in nearby Main Cave (MU-201). Another Montagu locality, (MU-203), yielded a small but interesting collection of fossils. Three types of fossiliferous matrix were encountered in Bed 3B. An extremely durable breccia was broken into pieces so that it could be transported through the narrow passages to the surface. Fossils were freed from thick flowstone rinds and a durable, calcined cave fill with the aid of an air hammer. Other fossils were obtained by exposing them in the softer fill of the floor of the cave.

The high clay content of the fill hampered attempts to employ screening. Bulk samples of fill were thus removed to the laboratory. A slurry of sediment and water was passed through a fine screen in order to sample small mammal remains.

The cave fill was methodically explored for fossil remains. The position and orientation of important individual finds and large concentrations of fossils were recorded in the field. Considerable amounts of fill and matrix remain undisturbed for further reference.

FAUNAL COMPOSITION

The fauna consists primarily of living and extinct species of macropodids. The Macropodinae are represented by *Thylogale* (indistinguishable from *billardieri*), *Macropus* (indistinguishable from *rufogriseus*), *Macropus titan* and the extinct wallaby *Protemnodon anak*. The Sthenurinae are represented by a large sample of *Sthenurus occidentalis* mandibles and maxillae. *Sthenurus* remains were second in frequency to those of *Thylogale billardieri* (figure 4b). *Macropus titan* and *Protemnodon anak* were rare. *Macropus rufogriseus* fossils were more common than *M. titan* and *P. anak* combined. Specimens of *Perameles gunnii* are also relatively common. While few individuals of *Vombatus ursinus* were present, the species provided some of the best preserved cranial remains from the site. The remaining eight species are represented by only one or two individuals each. Two individuals of *Zaglossus* sp. including one nearly complete specimen in partial articulation are among the more interesting fossils from the locality.

Sarcophilus harrisii is represented by a single canine tooth. The tooth is within the range of modern Tasmanian devils. A mandible of *Thylacoleo carnifex* from the "floor" site of Chamber B is the second example of this species recovered in Tasmania. The first specimen was found in Scotchtown Cave (Gill, 1954; Gill and Banks, 1956). A single individual each of *Potorous tridactylus*, *Mastacomys fuscus*, *Hydromys chrysogaster*, diprotodontids *?Zygomaturus*, *Palorchestes* and an otariid, (*Neophoca* sp.), represented by a lower canine, $P_{\bar{4}}$ and ?$M_{\bar{1}}$ (figure 5c) comprise the remainder of the fauna.

DETERMINATION OF THE EXTINCT SPECIES

This description is intended to give information sufficient to justify the species determinations presented. Detailed descriptions of the fauna are in progress for *Zaglossus* sp. and the Tasmanian Sthenurines.

MACROPODINAE

Macropus (Macropus) Shaw

Macropus (*Macropus*) sp.

Material: Juvenile left maxilla fragment containing P^2 unerupted P^3, DP^3 and M^1 (figure 6i, j).

Description: Slightly worn P^2, dumbell-shaped in outline, paracone smaller than metacone, separated by a deep lingual and shallow labial constriction, metacone and paracone joined on the labial side by a bifid crest that continues anteriorly into a preparacrista; small posterior cingulum unites with hypocone, crista connects anterior part of hypocone to posterior third of metacone; metastyle present on labial side. Slightly worn DP^3, molariform; high, relatively narrow anterior cingulum sloping lingually; lingual fossette usually present in *M. giganteus* reduced to a crease; midlink strong, expanded lingually and labially in its central portion; lingual valley narrower than in *M. giganteus*. Unerupted P^3, dumbell-shaped in occlusal outline; paracone separated from metacone by a well defined labial and shallow lingual constriction that divides the longitudinal crest extending between the two cusps; paracone comprises anterior third of tooth; prominent low cusp is present on the lingual side of the paracone (absent in

M. giganteus sample employed here); crista connects metacone to hypocone, hypocone relatively larger than forms of *M. giganteus* sample; shallow posterior fovea formed by the posterior cingulum. Slightly worn M^1, morphology as for *M. giganteus* except for narrower anterior cingulum and reduction of the lingual fossette, probably as a result of wear.

The specimen is difficult to assign due to its intermediate size between *M. giganteus* and *M. titan* (Table 1). The apparently relatively larger P^2, P^3

Table 1. Measurements of maxillary dentitions

	P^2		P^3		DP^3		M^1	
	Length	Max. width	Length	Max. width	Length	Width prot.	Length	Width prot.
Montagu	8.1	5.9	8.9	5.0	9.5	7.5	10.8	8.0
M. giganteus, Tas.	-	-	-	-	9.1	7.2	10.7	8.3
M. giganteus, Tas.	7.5	5.5	8.2	3.9	9.4	7.1	11.3	8.2
M. giganteus	6.3-	4.2-	6.6-	3.1-	7.8-	5.8-	8.7-	6.7-
(Bartholomai, 1975)	7.7	5.4	8.3	4.8	9.5	7.1	11.0	8.6
M. titan, QL.	9.2-	6.6-	8.5-	4.8-	10.1-	7.9-	10.6-	8.2-
(Bartholomai, 1975)	9.8	7.3	11.6	6.3	11.8	9.3	14.7	10.7

and DP^3 to M^1 ratio in the Montagu specimen is not significantly different from either species (Table 2).

Table 2. Ratios of lengths of maxillary dentitions

	P^2 / M^1	DP^3 / M^1	P^3 / M^1
Montagu	.75	.88	.82
M. giganteus, Tas.	-	.85	-
M. giganteus, Tas.	.66	.83	.79
M. giganteus, QL.	.70-	.86-	.76-
(Bartholomai, 1975)	.72	.90	.96
M. titan	.87-	.80-	.79-
(Bartholomai, 1975)	.92	.95	.80

A possible difference is in the ratios obtained for the maximum width of the same teeth (Table 3).

Table 3. Ratios of width of protoloph of maxillary dentitions

	P^2 / M^1	DP^3 / M^1	P^3 / M^1
Montagu	.74	.94	.63
M. giganteus, Tas.	-	.87	-
M. giganteus, Tas.	.67	.87	.48
M. giganteus, QL.	.63-	.83-	.46-
(Bartholomai, 1975)	.63	.87	.56
M. titan, QL.	.68-	.87-	.58-
(Bartholomai, 1975)	.80	.96	.59

In this regard the Montagu specimen resembles *Macropus titan* by having slightly higher ratios for all teeth measured than *M. giganteus*. The marginally more robust dentition, the presence of a well developed metastyle on the P^-, the lingual cusp on the paracone of P^3 and the slightly higher anterior cingulum suggest that the individual may be a very small *Macropus titan*. Differentiation of the two species is problematical because they are morphologically very similar. Bartholomai (1975: 205) found minor character differences for the lower dentitions but not the uppers. The major difference is size.

Macropus (*Macropus*) *titan*, Owen 1858

Material: Unworn fragment of left I_1, fragment of the anterior portion of a juvenile mandible containing a partially erupted I_1 and slightly worn P_2 (figure 6c, g, h).

Description: I_1 unworn, morphologically similar to *M. giganteus*, deep and thick; diastema very short (25.0 mm) due to the young age of the individual; symphysis deep, rugose; P_2 convex lingually; ridged anterior cuspid gives rise to a short longitudinal crest; crest terminating in a well-developed posterolabial cuspid; small cuspule present low on the margin of the crown in the mid lingual area; large posterolabial cusp formed by cristid extending from the small cuspule. The specimen is within the size range for *Macropus titan* (Table 4).

Table 4. Measurements of the mandibular dentition of *M. titan* (mm)

	I_1		P_2	
	Depth	Thickness	Length	Max.width
Montagu	12.2*	6.5*(est)	8.1	4.6
M. giganteus, Tas.	9.5	5.2	6.2	3.0
M. giganteus, Tas.	10.0	5.2	-	-
M. giganteus, QL. (Bartholomai, 1975)	-	-	5.3-7.0	2.8-4.0
M. titan, QL. (Bartholomai, 1975)	-	-	7.3-9.0	3.6-4.9
M. titan, Tas.	13.5	7.5	-	-

* Less than maximum as incisors are partially erupted

Protemnodon, Owen 1874
Protemnodon anak, Owen 1874

Material: Two right juvenile hemimandibles containing P_2, DP_3, M_1: right and left juvenile hemimandibles containing DP_3, M_1, M_2; juvenile maxilla with right and left P^2, DP^3, M^1, M^2; two isolated right second lower premolars and three incisors (figure 6a, b).

Description: P^2 oval in occlusal outline, paracone less broad than metacone; labial cingulum ascends apex of paracone producing an oblique, sharply defined ridge on the anterolabial side of the tooth; mid-labial side of tooth concave; short, strong sparsely decorated metacrista joins paracone and metacone; small shallow anterolingual fossette continuous with broader shallow fossette sub-round in shape; hypocone well developed, connected by an obliquely directed crista to the metacone; lingual cingulum low, constricted, defining the paracone and metacone. DP^3 molariform, sub-trapezoidal in occlusal outline; anterior cingulum low, sloping lingually; forelink absent; labial ridge ascends paracone as a continuation of the anterior cingulum; anterior fossette shallow, widest labially; metaloph broader but more compressed mesoidistally than protoloph; midlink rather low, weak, ascends protocone from mid-inferior portion of metaloph; paracone and metacone connected by a crest defined by a faint crease on the inner side of the cusps. M^1 nearly rectangular in outline, metaloph is slightly broader than protoloph; lophs relatively higher than in DP^3; forelink absent; anterior cingulum broad, low, somewhat sinuous, forming a shallow fossette.

Metaloph more curved than protoloph; Midlink moderately high; median valley deeper and narrower on the lingual side; posterior cingulum well developed with a small fossette near the base of the middle of the metaloph. P_2 suboval in outline, twice as long as wide, planar or slightly concave lingually; labial side convex; mesial and distal cuspids joined by a ridge decorated with three small enamel bulges; bulges separated by corresponding broad, shallow grooves lingually; cingulum defines a small crease or fossette anterolabially as it ascends the paraconid. DP_3 molariform, subtriangular in occlusal outline, hypolophid broader than protolophid; anterior cingulum moderately high; forelink high and prominent, curving slightly to ascend the protoconid from the labial side of the anterior cingulum; small labial and large lingual fossettes are present; midlink is low, weak, ascends hypoconid from a point slightly lateral to the mid point of the base of the protolophid; weak posterior cingulum. M_1 rectangular in outline; anterior cingulum broad; strong, short forelink expands distally from near the midline to ascend the protoconid; large labial fossette and larger lingual fossette are present on either side; protolophid and hypolophid approximately equal in width; midlink low; weak posterior cingulum.

Table 5. Measurements of upper and lower dentitions of *Protemnodon anak*

		P^2		DP^3		M^1	
		Length	Max. Width	Length	Width Prot.	Length	Width Prot.
Montagu	-	11.7	8.0	11.0	9.1	12.5	10.5
P. anak (Bartholomai, 1973)	-	11.6-13.5	6.3-7.5	10.7-11.8	8.0-8.8	10.7-13.3	9.1-11.2
	I_1	P_2		DP_3		M_1	
	Depth	Length	Max. Width	Length	Width Prot'd	Length	Width Prot'd
Montagu	13.1	10.5	5.1	10.1	6.0	12.2	8.1
P. anak (Bartholomai, 1973)	12.8-16.3	10.2-11.8	4.6-5.7	9.0-11.8	5.3-6.6	10.4-13.5	6.9-8.6

Prot. = protoloph; Prot'd = protolophid

The specimens of *Protemnodon* from Montagu conform closely to Bartholomai's (1973) description of the species. *Protemnodon anak* is also known from Scotchtown Cave, Smithton and King Island.

STHENURINAE

Sthenurus, Owen 1874
Sthenurus (*Simosthenurus*), Tedford, 1966
Sthenurus (*Simosthenurus*) *occidentalis*, Glauert 1910

Material: Right and left juvenile hemimandibles, left and right adult hemimandibles, nearly complete adult mandible (all with complete dentitions); left maxillary fragment with P^3, M^{3-4}; right temporal process of zygomatic arch; left M^{3-4}, left P^3, M^{3-4}; ?I^{1-3} (isolated); two lower incisors; isolated left P_3, two isolated right second premolars; metatarsals IV, one left and two right; probable postcranial material unassociated; (figure 7a, b, c.).

Description: These sthenurines can be differentiated from *Sthenurus* (*Simosthenurus*) *orientalis* (Tedford, 1966) on the basis of their 1) smaller size; 2) possession of a short anterior cingulum; 3) symphyseal union not extending posterior to P_3;

4) anterior root of the ascending ramus intersects the protolophid or is anterior to M_4 rather than posterior to it. The largest and most complete mandible is 156.5 mm maximum length. The height of the horizontal ramus posterior to M_1 is 47.3 mm. The dentitions are indistinguishable from *S. occidentalis* except for a slight proportional difference between length and width of the molars and a proportionally smaller P_3. They resemble *Sthenurus orientalis* only in respect to the relative decrease in the size of the P_3 to the molars.

Table 6. Measurements of the lower dentitions of *Sthenurus*

	P_3				M_1			M_2			M_3			M_4		
	L	AW	PW	HC	L	AW	PW	L	AW	PW	L	AW	PW	L	AW	PW
Montagu	15.1	7.2	10.0	8.5	10.7	9.5	9.9	11.7	10.5	10.6	12.8	11.1	11.0	12.0	11.0	9.9
Sthenurus occidentalis 45093(MC)	16.1	8.1	10.7	10.4	12.3	9.1	9.5	12.6	10.1	10.2	13.1	10.5	10.6	12.3	10.3	9.8
Sthenurus orientalis AMF 10201 (Tedford 1966)	17.0	7.9	10.7	8.4	14.0	10.9	11.2	15.0	12.2	12.7	15.2	13.0	13.2	14.6	12.7	12.1

L = length; AW = anterior width; PW = posterior width

DIPROTODONTIDAE

? *Zygomaturus* and *Palorchestes* sp.

Material: Fragment of left mandible with P_3 (figure 6f); right I_1.

Description: P_3 exhibits light wear on the paraconid; the tooth is subtriangular in occlusal outline; large paraconid comprises the anterior half of the tooth; protoconid extends approximately half as high as the paraconid, metaconid lower than protoconid; faint ridge defines a forelink that descends abruptly into a weak anterior cingulum; prominent bifid crest connects paraconid to protoconid; a low rounded crest descends from lingual side of paraconid to form a broad shelf on the metaconid; posterior cingulum low and broad; ectocingulum descends from protoconid extending to base of paraconid; labial side superior to the ectocingulum is distinctly concave.

Table 7. Measurements of ? *Zygomaturus* P_3

Length	Maximum Width	Height Crown
16.7	14.1	14.1

The specimen is similar to but smaller than P_3's of *Zygomaturus tasmanicum* (? = *trilobus*) from King Island and Mowbray Swamp (identified as *Nototherium victoriae* and *N. tasmanicum* in the Queen Victoria Museum collection). It is considerably wider than any species of *Palorchestes* but is within the range of *P. azael* for length. This greater width is due to the triangular outline of the tooth which contrasts with the oval outline of palorchestine lower premolars. The possibility of the tooth being a Dp_3 is ruled out by the absence of a developing P_3 crown and by the long, stout roots which extend down to the incisor

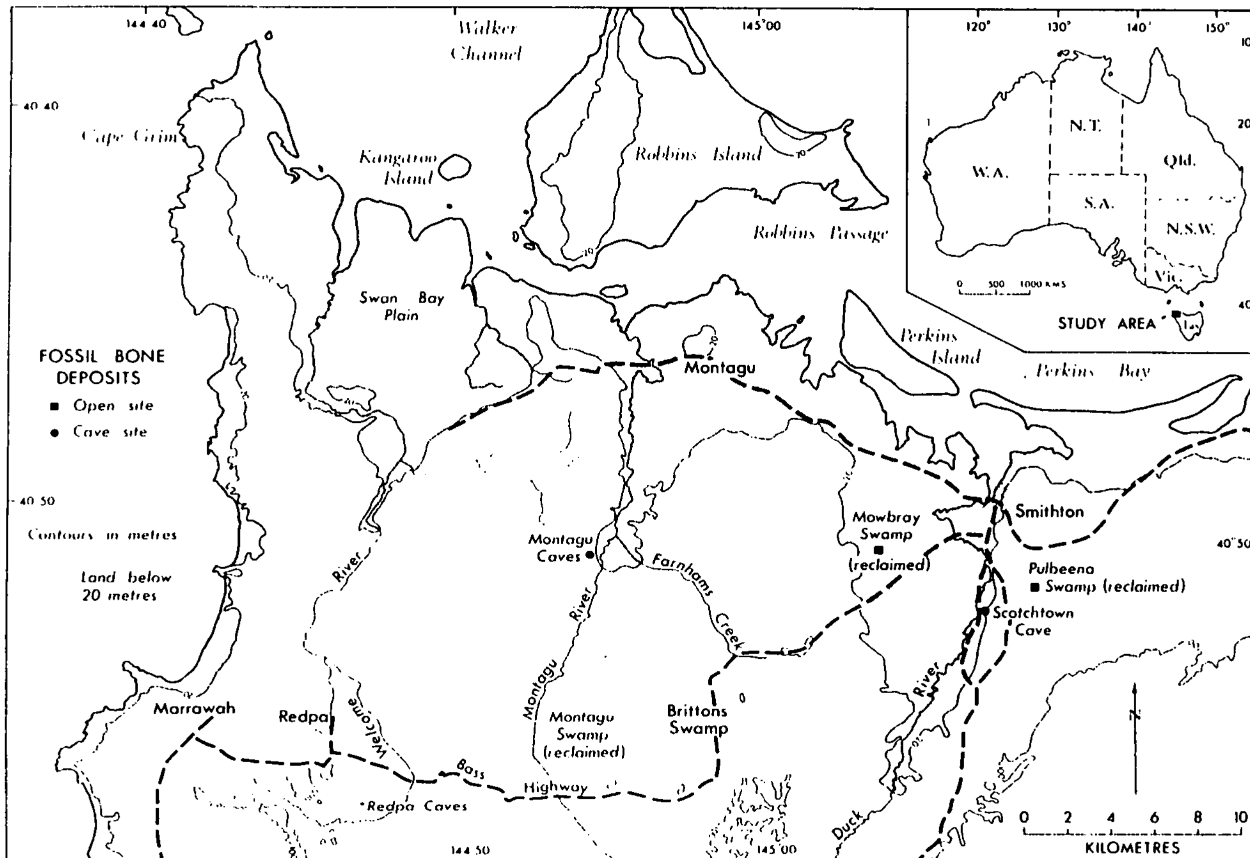


Figure 1   Location map of northwestern Tasmania

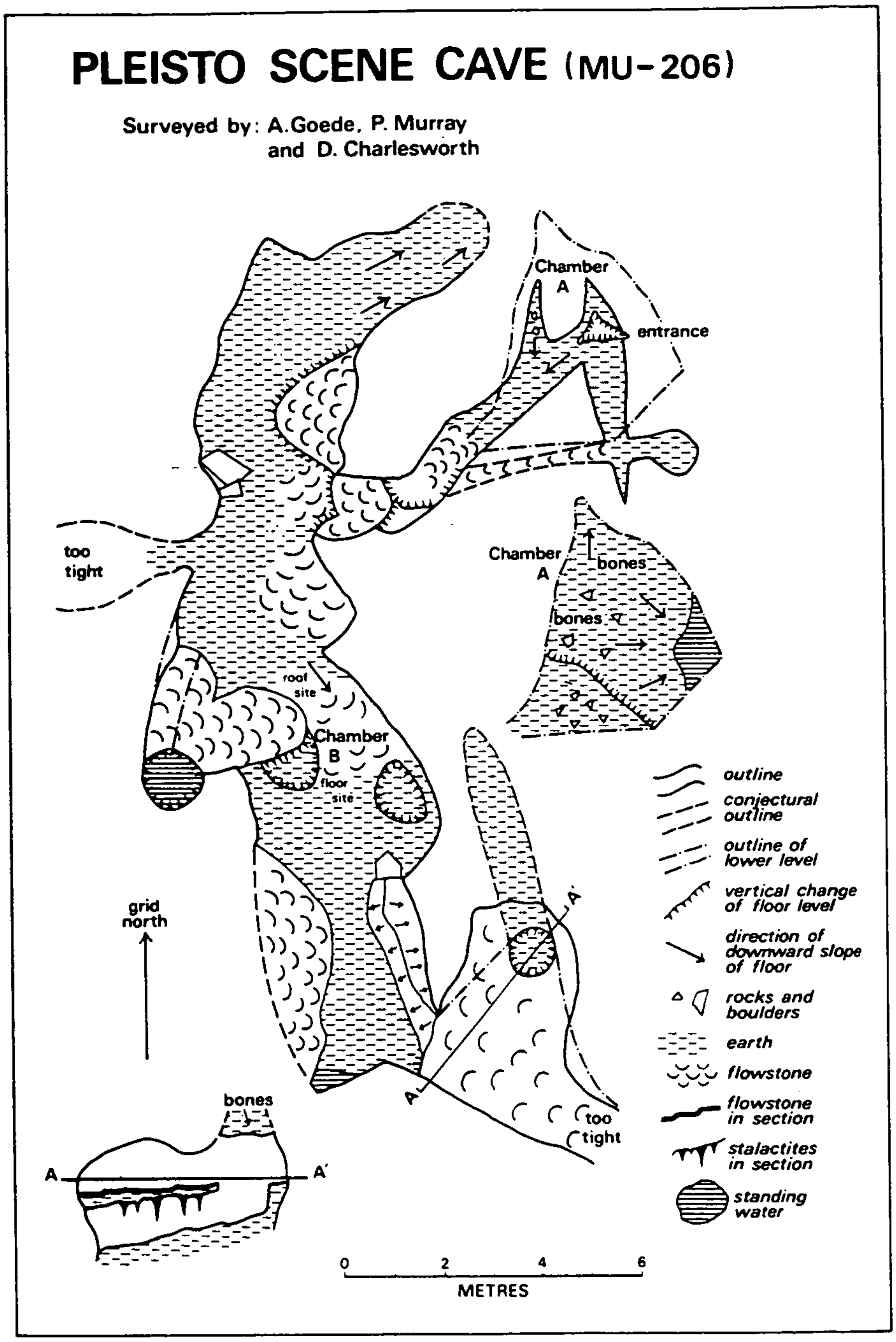


Figure 2 Survey of Pleisto Scene Cave, Montagu

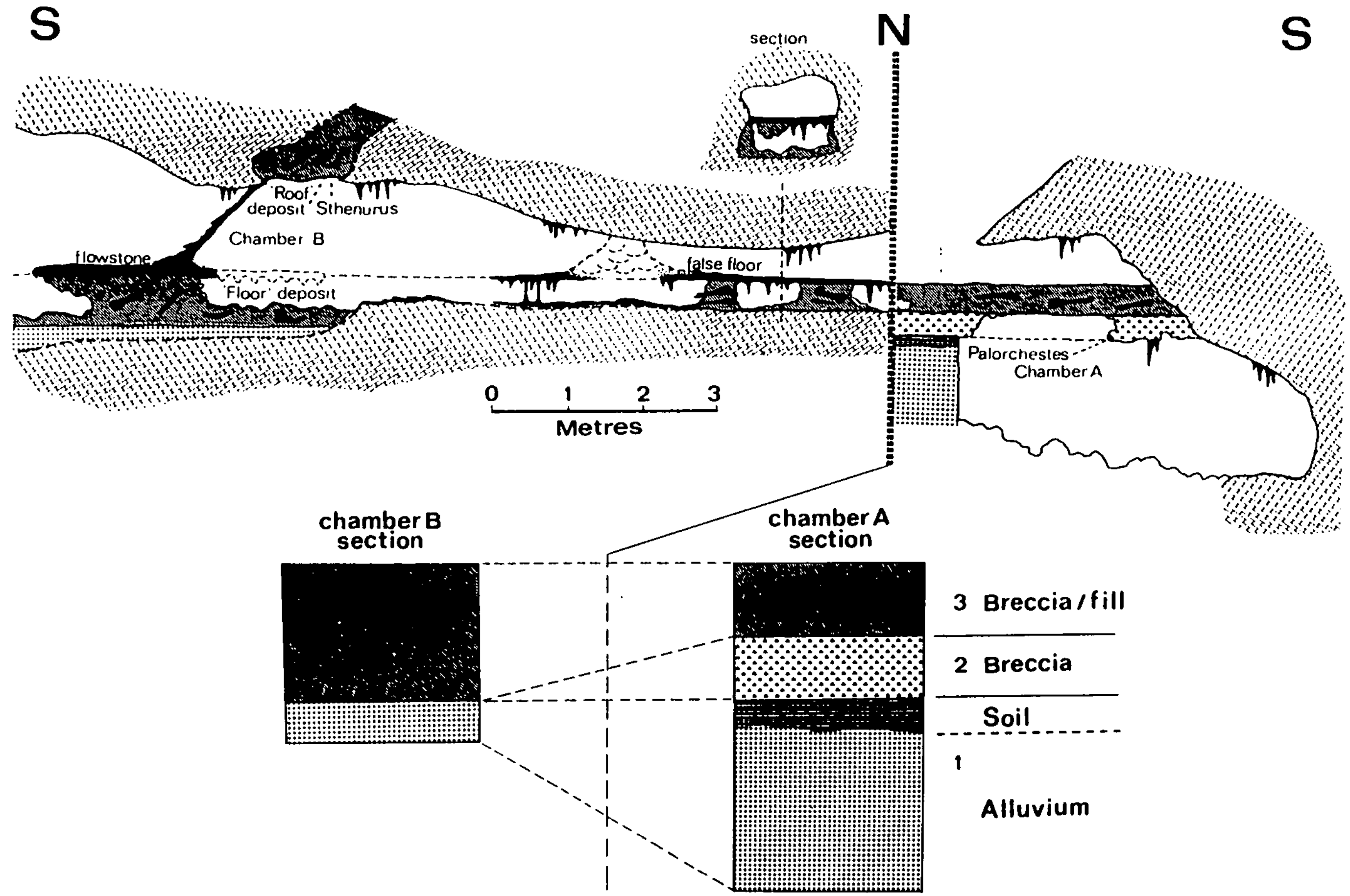
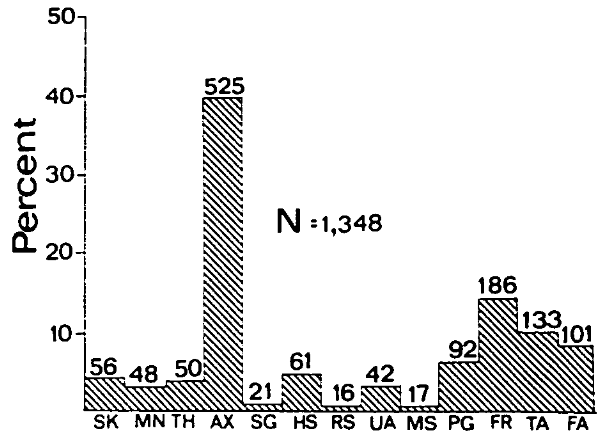
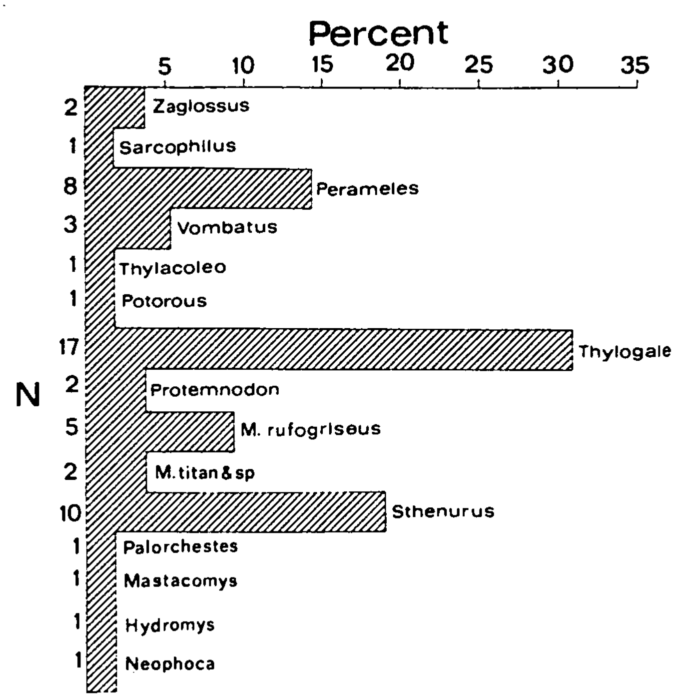


Figure 3 Diagramatic drawing of the stratigraphy of Mu-206. Chamber A is reversed in its long axis to aid in showing stratigraphic continuity with Chamber B. Diagram below shows inferred stratigraphic relationships between the two chambers. Note the absence of Bed 2 in Chamber B.



a



b

Figure 4 a Proportion of all identifiable bones expressed as a percentile histogram. The graph shows all fragments prior to assessment of a minimum number. Bold numerals indicate the number of each element recovered. SK, skull; MN, mandible; TH, teeth; AX, axial (ribs and vertebrae); SG, shoulder girdle; HS, humerus; RS, radius; UA, ulna; MS, manus; PG, pelvic girdle; FR, femur; TA, tibia; FA, fibula.

b Minimum number of individuals of each species from Bed 3B expressed as a percentile histogram. Bold numerals give the minimum number.

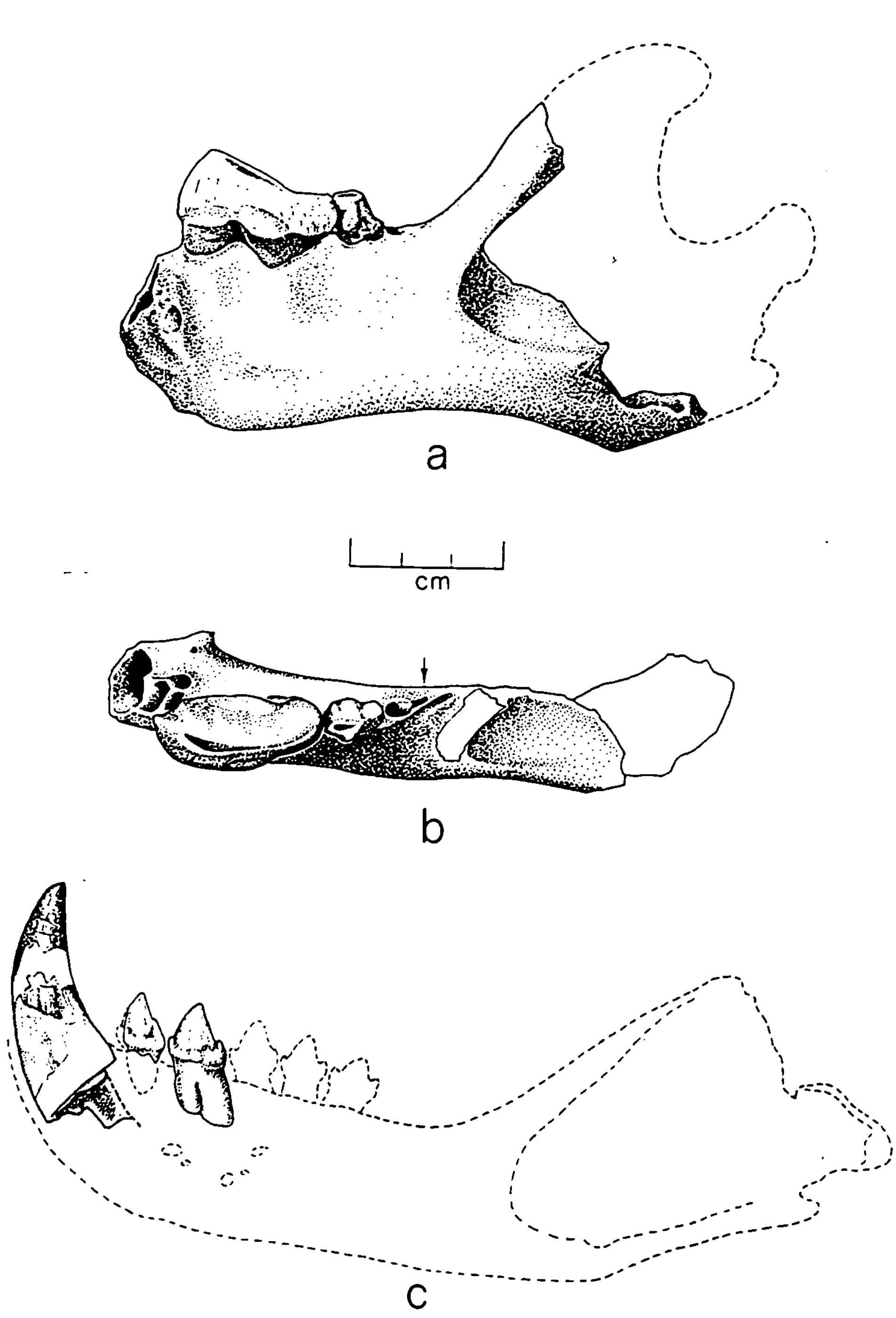


Figure 5 a Side view of left hemimandible of *Thylacoleo carnifex*, ascending ramus restored.

b Occlusal view of mandible. Arrow indicates possible M_3 alveolus.

c Left canine, P_4 and M_1 of *Neophoca*. Scale equals 3 cm.

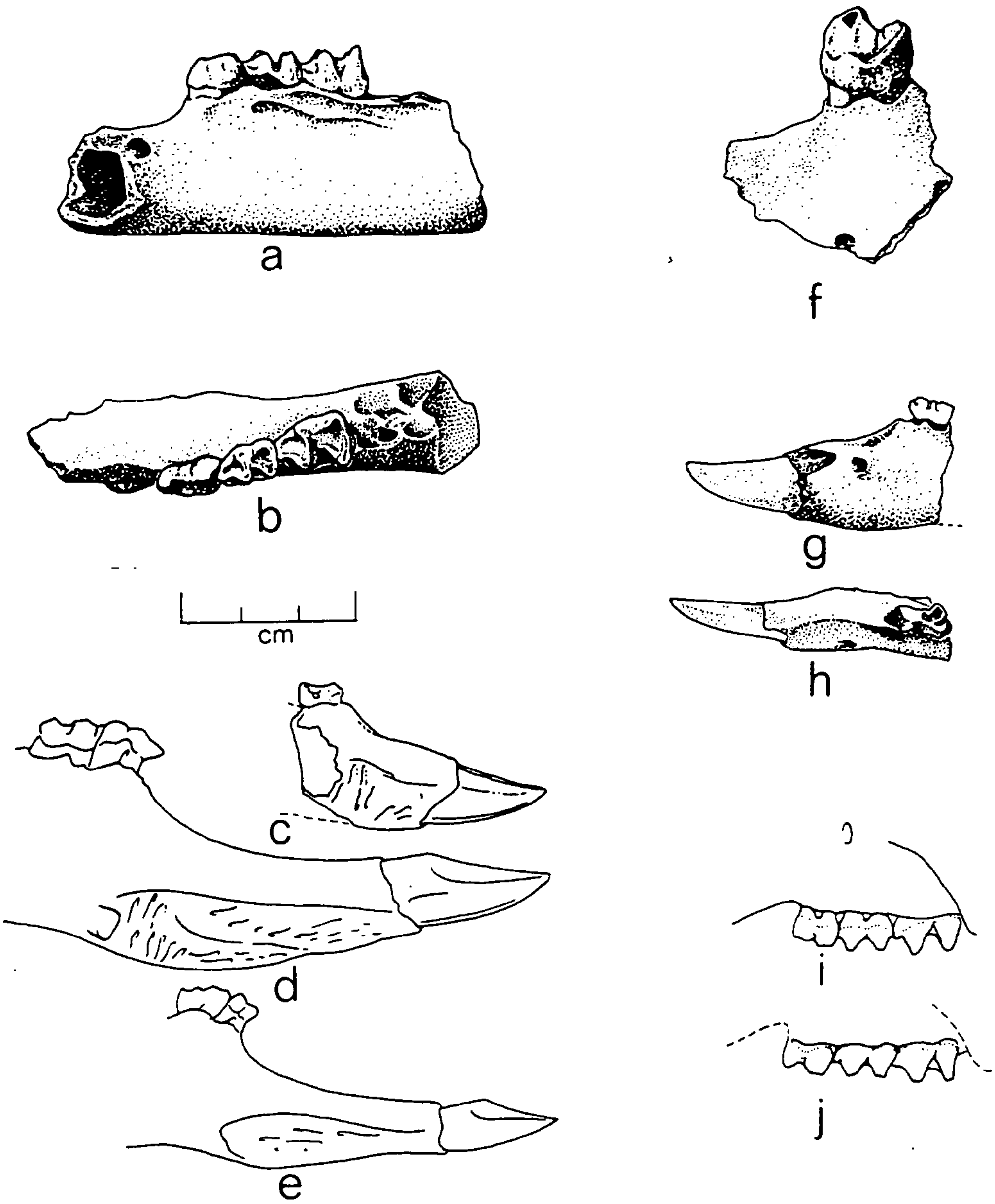


Figure 6 a Left mandibular fragment of *Protemnodon anak*.
b Occlusal view showing P_2, DP_3 and M_1.
c Outline of *Macropus titan* mandible fragment from Montagu compared with
d *M. titan* (Florentine Valley).
e *Macropus giganteus* (Ross, Tasmania).
f Left P_3 of unidentified diprotodontid (*?Zygomaturus*).
g Labial side of mandible of *Macropus titan*.
h Occlusal view.
i *Macropus giganteus* P^2, DP^3 and M^1 from Ross, Tasmania compared with
j *Macropus* sp., Montagu.

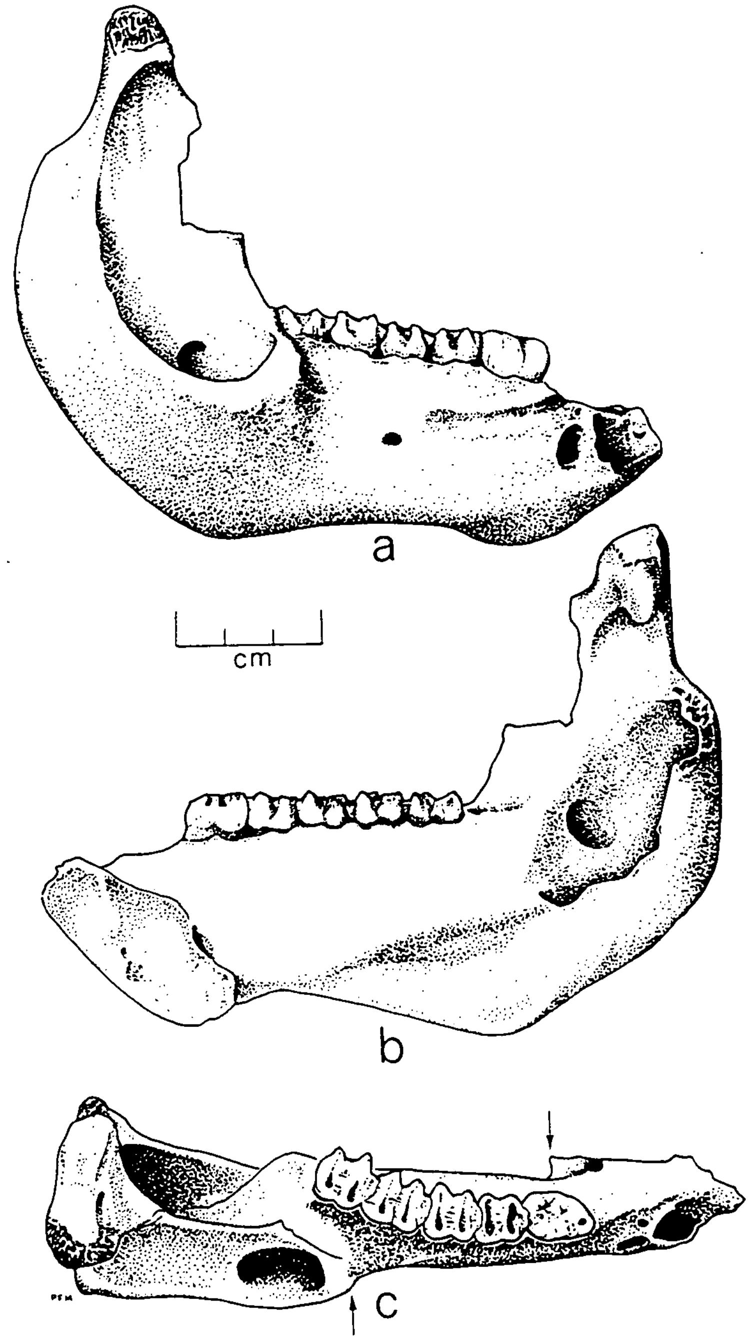


Figure 7 a Labial view of right hemimandible of *Sthenurus occidentalis*.

b Lingual view.

c Occlusal view. Arrows indicate posterior margin of mandibular symphysis and the anterior root of the ascending ramus. Dentition is P_3, M_1-M_4.

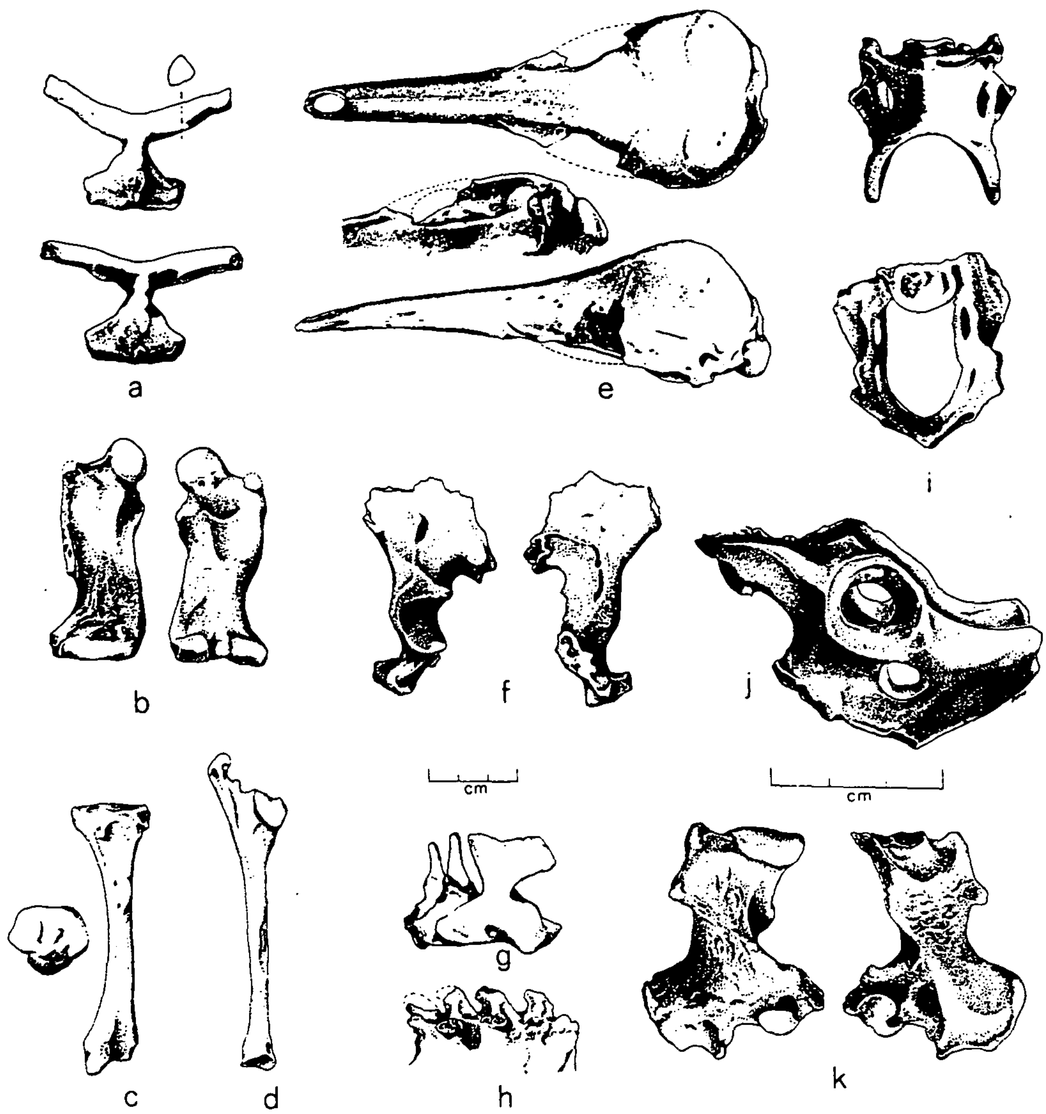


Figure 8 *Zaglossus* sp.

a Episternum and clavicles.
b Right femur.
c Right tibia.
d Left fibula.
e Cranium.
f Right scapula.
g Axis, C3-4.
h Thoracic vertebrae.
i Ventral and frontal view of pelvis.
j Side view of pelvis, enlarged to show detail.
k Right humerus.

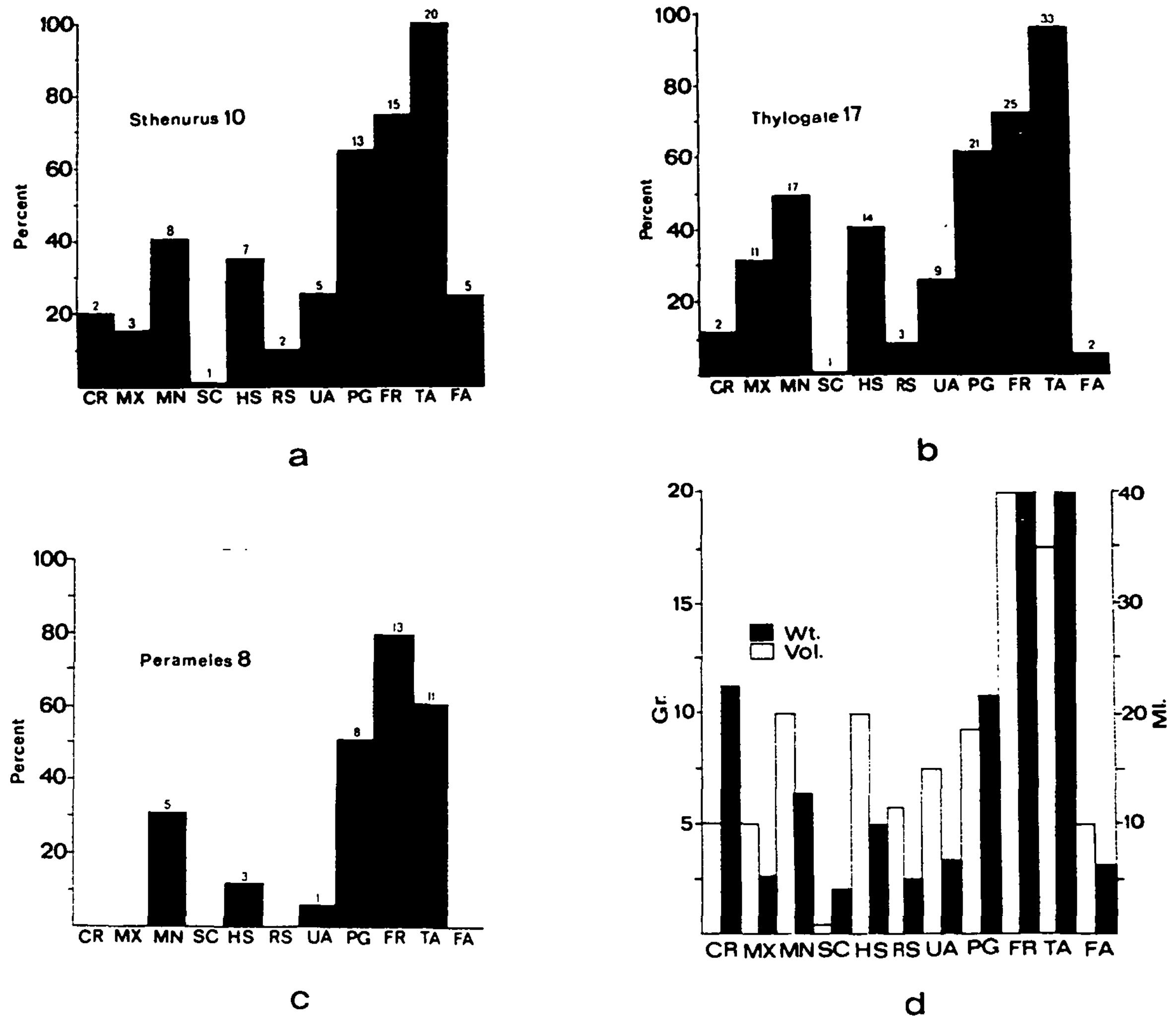


Figure 9 a Percentile histogram expressing differential preservation of skeletal elements in *Sthenurus occidentalis* (certain post-cranial elements are only tentatively assigned to this species). Axial elements have been omitted. One hundred per cent is the expected frequency for each element shown, based on the minimum number of individuals, thus with ten individuals present, there should be a total of 20 specimens of any paired element of that species. Small numerals express the actual number of each element. CR, neurocranium; MX, maxilla; MN, mandible; SC, scapula; HS, humerus; RS, radius; UA, ulna; PG, pelvic girdle; FR, femur; TA, tibia; FA, fibula. Bold numeral = minimum number of individuals.

b Histogram expressing differential preservation of elements of *Thylogale*.

c Histogram expressing differential preservation in *Perameles*.

d Histogram showing the weight and amount of displacement volume of each element of *Thylogale*. Note the similarity in shape of all four histograms.

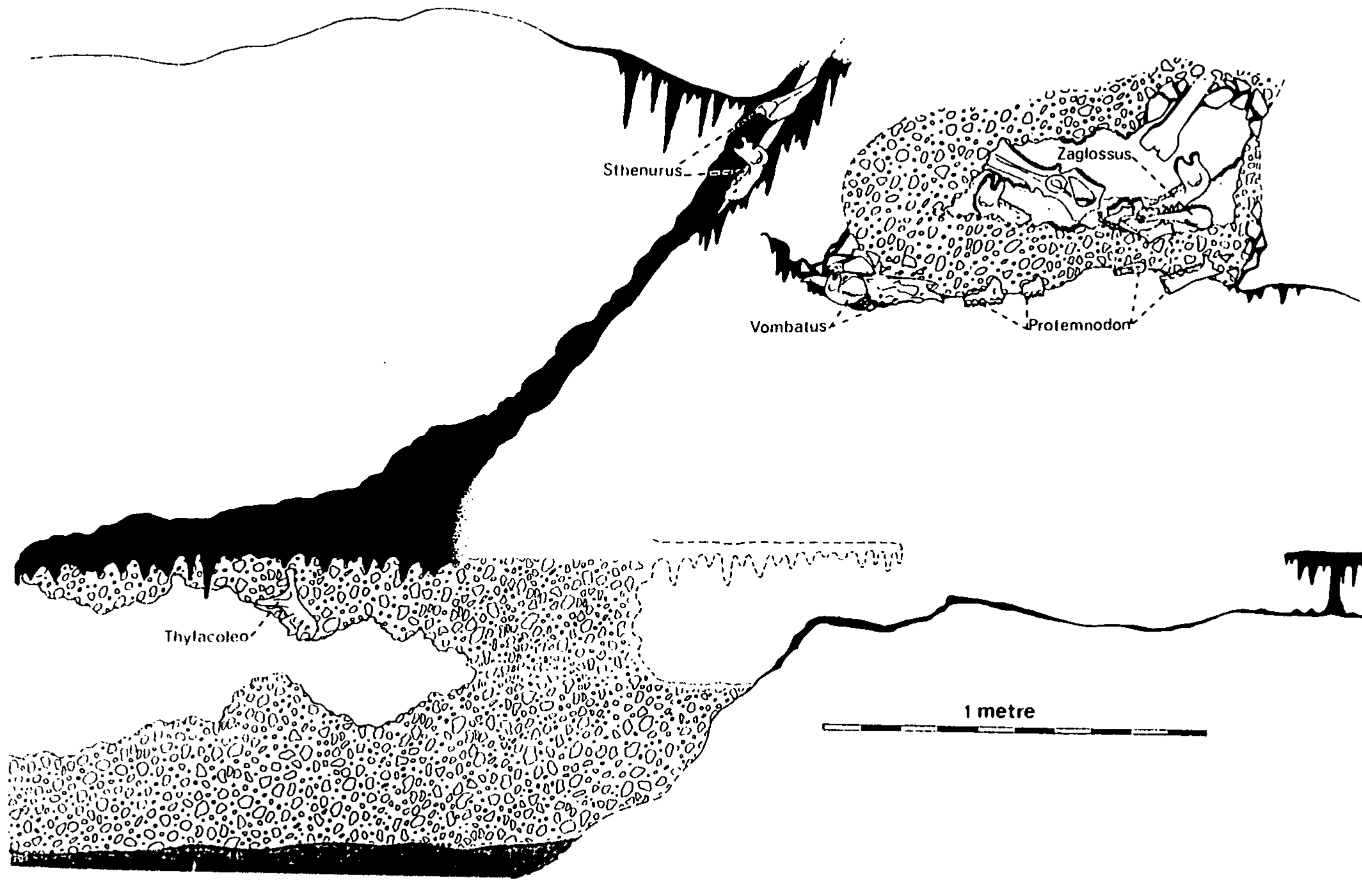


Figure 10 Semidiagramitic drawing of *in situ* fossils in Bed 3B. Scale is approximate, several different planes are depicted as one.

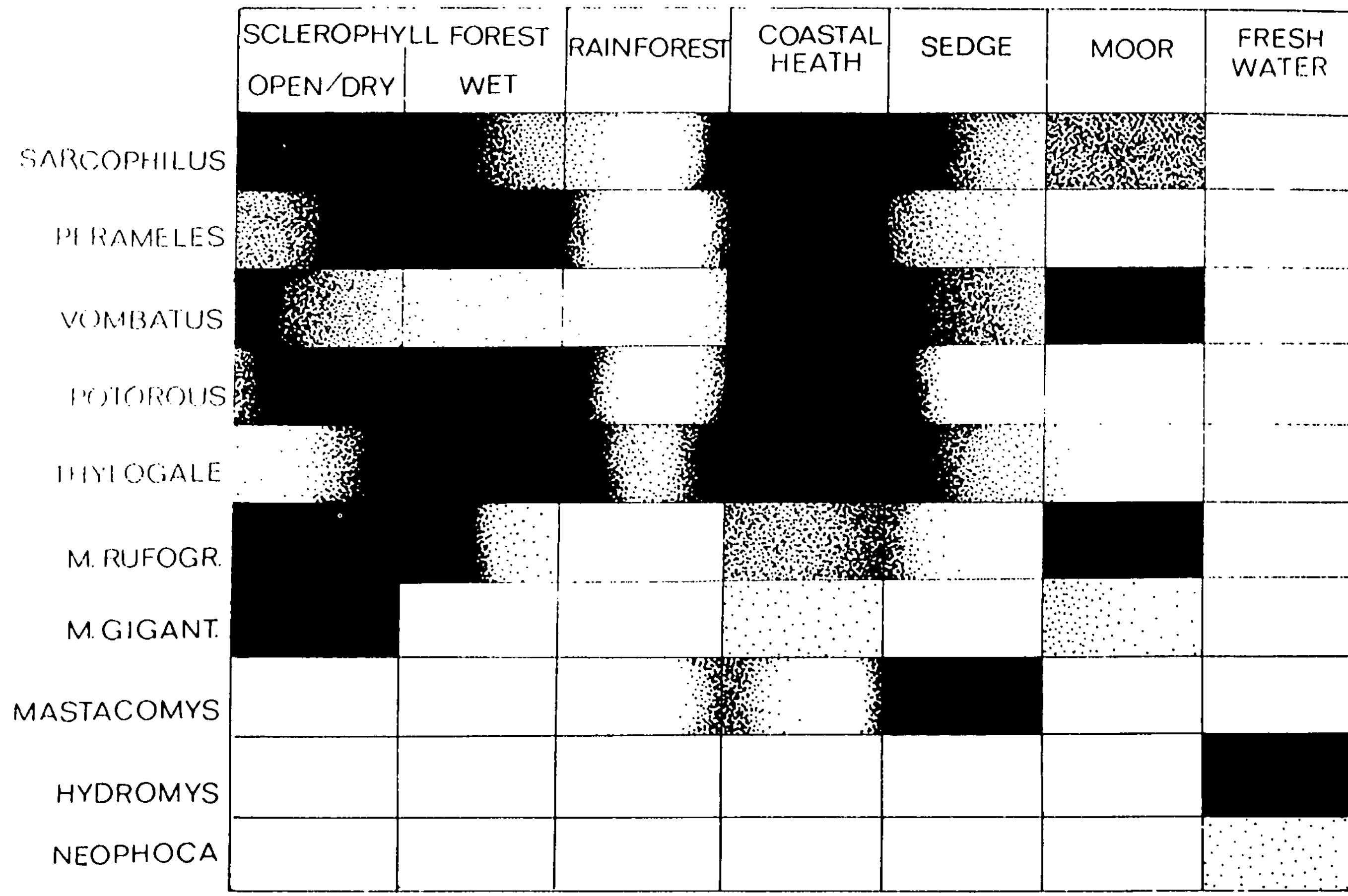


Figure 11 Habitats of living Tasmanian species recovered in Bed 3B. Preference is expressed by the pure black areas. Suboptimal and rare presence is shown by varying the density of stipples. Ecotones are expressed by continuity of shading between borders of listed habitats. All forms shown in rainforest areas are known to occur only on the verge or edge of the habitat.

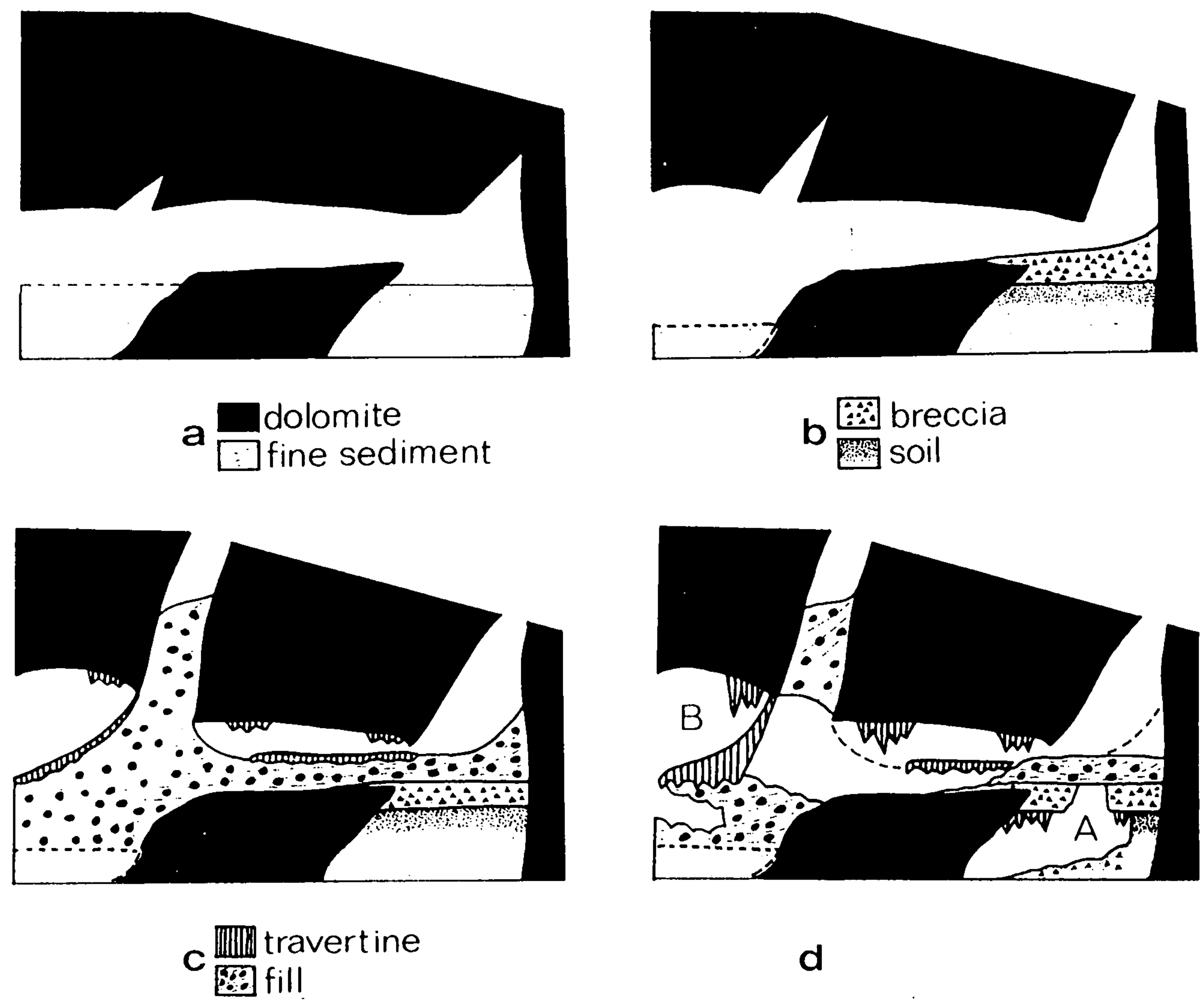


Figure 12 Sequence of events

a Initial alluvial sedimentation.
b Deposition of Bed 2 with the opening of the Chamber A entrance.
c Formation of debris cone, initial flowstone deposition.
d Present.

alveolus. The incisor roots were probably of large diameter. The diastema appears to have been short and the position of the mental foramen relative to the premolar agrees more with *Zygomaturus* than *Palorchestes*. A lower incisor from Bed 3B positively identifies *Palorchestes*.

Table 8. Comparison of measurements of P_3 from *Zygomaturus* and *Palorchestes*

	Length	Maximum Width	Ratio W/L
Montagu ? *Zygomaturus*	16.7	14.1	.84
Tas. Mus. *Zygomaturus*	20.1	16.2	.81
Palorchestes painei (Woodburne, 1967)	12.3	8.3	.67
Palorchestes parvus (Woods, 1958)	14.9	10.6	.71
Palorchestes azeal (Woods, 1958)	17.4	10.4	.60

THYLACOLEONIDAE

Thylacoleo carnifex, Owen 1859

Material: Fragment of horizontal ramus containing P_3 and M_1 (figure 5a, b).

Description: This is a young small adult individual with moderate wear on the P_3 and M_1. It is distinguished from typical specimens of *Thylacoleo carnifex* in possessing a narrow, shallow alveolus posterior to the M_2. This may represent the socket of a tiny third molar.[2] The length of the P_3 crown of the Montagu specimen is also relatively short, perhaps in association with the presence of a third molar. A comparison of Tasmanian and Mainland specimens is given in Table 9.

Table 9. Measurements of *Thylacoleo carnifex* mandibular dentitions

	Depth ramus Posterior top P_3	Length Crown P_3	Length Crown M_1	Ratio M_1 / P_3
Montagu	39.5	32.5	11.5	.35
F745 (Woods, 1956)	50.0	40.7	-	-
F2927 (Woods, 1956)	44.0	-	13.7	-
F2929 (Woods, 1956)	44.0	39.3	13.2	.34
F748 (Woods, 1956)	37.0	35.3	11.9	.34
F2928 (Woods, 1956)	44.0	39.2	13.8	.35

Table 10. Measurements of *Thylacoleo carnifex* from Montagu

Symphysis L x W	Thickness ramus at P_3	Thickness ramus at M_2	Incisor alveolus L x W	M_2 alveolus L x W	? M_3 alveolus L x W
24.0 x 25.0	19.2	15.[illegible]	20.5 x 9.4	4.4 x 3.5	3.0 x 1.0

[2] Woods (1956: 140) noted a depression immediately posterior to the second molar of a specimen which he interpreted as the alveolus of a small M_3.

TACHYGLOSSIDAE

Zaglossus, Gill 1876
Zaglossus sp.

Materials: Skull lacking mandible, axis, cervical vertebrae 3-4, thoracic vertebrae 1-3 or 2-4; sacral vertebra 1, episternum, clavicles, sternal fragments, ribs, right and left humeri, fragment of additional left humerus, two right scapulae, and one left scapula, right and left femora, right and left fibulae, right and left tibiae and innominate bones missing the ilia (figure 8).

Description: Sufficient information for the recognition of the genus is provided by figure 8. The femur of a similar form was described by Scott and Lord (1922) as a new species, *Zaglossus harrissoni*. The skull of the Montagu specimen is within the metric range of living *Zaglossus bruijnii* and it is morphologically similar to that species. Specimens described by Dun (1895)[3] and Glauert (1914) as *Zaglossus hacketti* are considerably larger than the Tasmanian form. Material from Mammoth Cave has certain morphological differences in addition to size that distinguish it from the Montagu form (Glauert, 1914).

Table 11.-Condylobasal lengths of *Zaglossus bruinjii* and *Zaglossus* spp.

Montagu	AMNH (Van Deusen, 1969) 190859	190862	190863	66194	194702	104020	105072	(Dun, 1895) Gulgong
165.0	203.0	186.0	193.0	168.0	154.0	180.0	158.0	265.0 (est.)

DISCUSSION

The Montagu Bed 3B fauna is similar to the assemblage from nearby Scotchtown Cave. The Montagu fauna lacks two additional *Sthenurus* species (*Sthenurus ?orientalis* and *Sthenurus ?andersoni*) recently identified in the Scotchtown Cave material (P. Murray, in preparation). Both Montagu and Scotchtown Cave contain a subspecific variant of *S. occidentalis* distinguished from the type by the characters given in the fauna description section of this paper.

PRESERVATION

A sample of 1,348 identifiable elements were analysed. The overall pattern of elements recovered indicates a predominance of limb bones and axial elements (figure 4a). Larger animals are more common than smaller ones.

Significant differential preservation was detected by noting the relative scarcity of small mammal remains and small skeletal elements of larger species in the screened bulk samples. The factor of differential preservation was tested by statistical examination of the remains of the most common species in the assemblage: *Thylogale*, *Sthenurus* and *Perameles*. A minimum number of individuals for each of these species was determined. This permitted the establishment of an expected frequency of all other skeletal elements for the bones belonging to that particular species. The observed frequency for each bone was then expressed as a percentage of the expected frequency (figure 9a, b, c, d). The shape of each histogram is remarkably uniform for each of the three species. Tibiae, femora and pelvic elements predominate. Mandibles are relatively common. Rare are scapulae, neurocrania, fibulae and radii. Differential preservation may have been due to the gradual decomposition of the less massive bones. Assuming that the robustness of each bone could be expressed in weight, a sample of *Thylogale billardieri* bones were weighed and plotted. The

3 Dun may have greatly overestimated the length of the skull of his specimen. An estimate based on the Montagu skull presents a figure closer to 180 mm total length for the Gulgong *Zaglossus*.

relative compactness or surface area of each bone was estimated by measuring the amount of fluid displaced.

These findings were scaled to the size of the expected frequency histograms for ease of comparison (figure 9d). The close correspondence of the weight/displacement histogram to the shape of the histograms of observed frequencies of elements clearly suggests that the lighter and thinner the bone, the less likely its preservation.

POSSIBLE CAUSES OF FAUNAL ACCUMULATION

Caves are among the best environments for the accumulation and preservation of bones of Recent and Pleistocene animals (Kurten, 1968). The most frequent causes for fossil deposits in caves include use of the cave entrance as a human occupation site, with the bones representing food refuse; the occupation of the cave by hibernating animals (Kurten, 1968), and the use of the cave by carnivores and scavengers, in which case there are remains of its prey, and sometimes remains of the responsible carnivore.

Many caves have treacherous vertical shafts leading to the surface forming natural pitfalls that may trap unwary animals. Animals may be attracted to karst areas because cave openings and overhangs offer shelter. Certain food plants may also grow more prolifically on the carbonate rich soil of the limestone exposures.

THE DEBRIS CONE

Evidence from stratigraphy and geomorphology combined with the statistical analysis of the fauna indicates that the Bed 3B deposit is the remains of a debris cone. The eroded remains of this fan of extraneous sediments originate from the steeply inclined shaft leading to the surface. The entrance of this shaft or fissure has been choked by soil and debris and its exact location is unknown. We have determined however, that the material in the roof is not a clinging remnant of a previously choked horizontal passage. This helps to rule out the possibility that the fossils and sediments were washed in by stream activity.

Configuration of flowstone sheets indicates the original shape of the debris cone (figures 3, 10). In the "floor" site, the greatest concentration of fossils is along the walls in the lowest deposits of cave fill. The debris cone was located in the centre of a rather narrow passage, where erosional activity was concentrated. The deposit gravitated to the sides of the chamber and small recesses in the floor.

CAUSES OF BREAKAGE OF THE BONES

The fossil bone from Bed 3B is permineralized, brittle and often deeply stained with mineral salts. The preservation of bone is extremely poor in the clay-rich sediments (Bed 1B) near the base of the exposed Chamber B "floor" deposit. Excellent preservation of bone is found in the "roof", from the "floor" breccia and from loose stony fill beneath. Nearly all of the specimens are coated with hard calcined matrix. Broken material is common. Ribs are invariably fragmented, as are some of the more robust long bones. Breaks in long bones tend to follow the alignment of osteons. The delicate processes of vertebrae are frequently missing. A *Protemnodon* mandible in the roof deposit appears to have been sheared. Other "sheared" long bones could be seen throughout the deposit where the matrix was undercut by erosion, causing a portion containing part of the specimen to fall under its own weight. Most of the fractures appear to be clean, post-depositional breakage caused by slumping, faulting and creeping of the matrix. Considerable slow, low energy movement of the deposit is indicated.

A few broken bones suggest that damage occurred at the time of deposition. These breaks are characteristic of fresh bones. Spiralled breaks with bevelled and hinged edges may have been caused by the impact of the animal's fall down the shaft.

Evidence of activity of carnivores and scavengers is also present. Three or four specimens have rodent tooth marks and one is extensively damaged by gnawing. A single *Macropus rufugriseus* tibia shows definite evidence of having been chewed on its proximal and distal ends by a larger carnivorous species. Some bird remains (*Rallidae*) show evidence of chewing on the extremities of long bones. These were probably chewed by small scavengers or carnivores. Emu remains are undamaged.

The bulk of the fossil material appears to have been unharmed by scavengers or carnivores. Many of the typical signs of carnivorous activities are absent: the ascending rami are present in many of the mandibles, the epiphyseal regions of long bones tend to be undamaged. The bones of small animals when present, tend to be whole and unmarked. Characteristic tooth marks of carnivores are uncommon (see Douglas, *et al.*, 1966).

The balance of evidence indicates that the fossil remains resulted from animals falling into a steeply inclined shaft. Some scavengers and carnivores may have been attracted by the presence of other trapped or decaying animals. It is probable that animals capable of scrambling could move in and out of the shaft. This would be particularly likely in the case of rodents, small dasyurids and *Sarcophilus harrisii*. All are exceptional climbers. Terrestrial birds such as emus and native hens would be expected victims of the pitfall. The lack of other birds, passerines, ducks and plovers, also tends to favour the secondary role of carnivore activity as a source of the fossils. A wide range of birds would be expected if this were to represent the refuse of active carnivores.

PATTERN OF REPRESENTATION

A final argument that tends to rule out carnivorous activity as a primary cause of the bone accumulation in Bed 3B is found in the pattern of representation of skeletal parts. Bone accumulations resulting from the activity of carnivores appear to have a different pattern of representation to that found in Bed 3B. An interesting faunal analysis of a South African site (Swartklip I) by Klein (1975) provides an excellent example. At Swartklip I and Makapansgat the proportion of femora and tibiae is relatively much lower while mandibles are considerably more frequent. Other elements show a similar, rather great discrepancy in relative abundance between the South African sites and the Tasmanian one. In addition, Klein found a quite different ratio between proximal and distal ends of certain long bones. In Bed 3B these are in approximately equal proportions. Fractures are also less frequent in the Montagu deposit.

ECOLOGICAL IMPLICATIONS

The most common living macropodine species represented as fossils in Bed 3B (*Thylogale, M. rufogriseus*) are presently widely distributed and are associated with many different communities. *Thylogale billardieri* prefers damp areas with dense vegetation. Fern gullies, the verges of rainforest and heathland in the presence of tall dense scrub, are favoured habitats (Green, 1974: 375) (figure 11). *Macropus rufogriseus* is found in habitats ranging from coastal heathland and rainforest verges, to open subalpine areas. It prefers drier areas of sclerophyll forest (Green, 1974: 375). *Macropus giganteus* prefers drier open sclerophyll forests (Green, 1974: 374). It is likely that *M. titan* also preferred open dry habitats. The high abundance of *Thylogale* in the deposit may reflect an optimum habitat for that species. The brush wallaby (*M. rufogriseus*) is somewhat intermediate between the two in its habitat preferences. Evidence from modern cave faunal accumulations shows that in optimum habitats for *Macropus giganteus* there is a greater frequency of that species than of either *Thylogale* or *M. rufogriseus* (P. Murray, unpublished data on caves at the Quoin, near Ross, Tasmania). This suggests that the fossil habitat was suboptimal for *Macropus giganteus* and by inference *M. titan*, and perhaps marginal for *M. rufogriseus*. This implies the presence of scrub, also perhaps wet conditions.

Perameles gunnii prefers open habitats with low ground cover (Heinsohn, 1966), in contrast to *Isoodon* which is more restricted to locally abundant dense wet scrub and coastal heath. *Perameles* is common in the deposit while

Isoodon is absent. This implies that the immediate area was relatively open.

The single specimen of *Potorous* suggests the presence of dense natural vegetation. The species is common in coastal heath communities and in areas with low, dense ground cover (Heinsohn, 1968). The relative scarcity of the species in the deposit suggests that the immediate area was more likely open than covered with dense scrub or forest. Its presence does suggest the existence of a scrub or densely vegetated area nearby, assuming that the cave mouth was within its home range.

The presence of *Mastacomys fuscus* in the assemblage suggests the possible presence of a wet, perhaps treeless sedgeland, its almost exclusive present habitat (Green, 1968, 1974).

The living species of *Zaglossus* is poorly known. It is presently confined to humid montane forests (Van Deusen and George, 1969).

Rails prefer wet areas with dense vegetation. *Tribonyx* occurs in grassy vegetation including the edges of swamps and creeks, and tussocks (Slater, 1970). Emus prefer open grasslands, savanna parklands and scrub.

Hydromys is associated with a wide variety of fresh and brackish water habitats (MacNally, 1960). The presence of both the water rat and *Neophoca* can be explained by the proximity of the site to the Montagu River. The proclivity for sea lions to ascend rocky prominences on which to rest and sun themselves suggests the likely course by which the animal became part of this otherwise non-littoral assemblage. *Neophoca* could also represent the prey of a carnivorous species. This still does not account for its inland occurrence. It is highly unlikely that the remains would be carried more than 10 km unless the teeth represent the durable contents of carnivore dung.

Habitat preferences of extinct species must be inferred on the basis of their morphology, or when possible, a combination of their anatomy and evidence from geomorphology or palaeobotany. *Sthenurus occidentalis* has low molar crowns and trenchant lophs characteristic of a browser. Its high abundance in Bed 3B indicates that a suitable leafy forage was locally available, perhaps in the form of heaths, scrub or a low, open forest community. Raven and Gregory (1946) suggest that *Sthenurus* was a forest-preferring species. The animal's large size and inferred locomotor capability does not favour a dense, closed forest of the type present today at Montagu.

The dentition of *Protemnodon anak* suggests that the animal was a grazer (Raven and Gregory, 1946). It is slightly more common than *M. titan*. The presence of *Protemnodon anak* and *Macropus titan* suggests that suitable grazing habitats were locally present.

The faunal evidence favours an open or partially open habitat with the presence of dense scrub, or digitations of low wet sclerophyll and/or rainforest. A formation consisting of wet hummock sedgeland with bordering scrub and forest associations, similar to those present in the northwest coastal area of Tasmania today would not be inconsistent. Grassland was probably present nearby. The greater compliment of macropod species in the Scotchtown Cave assemblage may be a reflection of the distal grassland community.

The fauna favours the interpretation that the habitat was wet, though perhaps not as wet as analogous modern coastal lowlands on the west coast of Tasmania.

SEQUENCE OF EVENTS

The following is an attempt to synthesize the geomorphological and palaeontological findings. The major stages of cave evolution and deposition of the sediments are summarized in figure 12a-d. The initial phase of sedimentation in the cave (figure 11a) has already been described. The accumulation of Bed 2 probably occurred at some time after a fissure had reached the surface. That fissure is now the entrance to the cave system. The production of the breccia probably took place during a cold dry phase. Some mammals had become trapped in the deposit in a manner probably not unlike their occurrence in Bed 3. Deposition of Bed 3 suggests a period when solution weathering of the dolomite was dominant over frost fracturing. The large amount of sediment, and the extent to which active movement of the material took place suggest a period of active cold climate soil mobilization. The tendency for the dolomite fragments to be larger and more rounded than in Bed 2 is consistent with a cold, wet environment. This agrees with the evidence from the fauna. More sediment and trapped animals continued to accumulate into a debris cone. A flowstone layer formed over the debris cone and its fan extending up and down the surrounding passages. Active creeping of the sediment took place throughout the depositional period which accounts for the extensive scattering and breakage of the fossils. The debris cone may have been partially eroded away at various times during this phase until the shaft became clogged and the sediments within consolidated by calcification. A final stage of erosional activity locally washed the sediment from beneath the flowstone layer leaving false floors.

AGE OF BED 3B

Radiometric dates: Bone collagen dates from Bed 3B suggest a possible terminal Pleistocene age for the deposit. Sample R5001/2 (N.Z.) from the floor of Chamber B yielded a ^{14}C date of 10,100 ± 200 years B.P. An apparently anomalous date of 1,450 ± 210 years B.P. [R5001/1 (N.Z.)] was obtained from the bone of an extinct species in the "roof" deposit. We suggest that the 10,000 year date is a minimum age for the site and that the anomalously young date is due to extensive replacement of the bone.

A terminal Pleistocene date is not incompatible with the stratigraphic evidence. The angular dolomite fragments in Bed 2 could be interpreted as the maximum cold phase of the second hemicycle of the last glaciation. Bed 3 dolomites are more rounded and larger, suggesting increased solution activity during a less cold and probably wetter climatic phase. Bed 3 may therefore represent the terminal Pleistocene or a late stadial. There is no deposit above Bed 3, even though the entrance to the system above Chamber A has apparently remained open since its deposition. This would support the inference that Bed 3 represents the final depositional phase of the last glacial stage.

SUMMARY

The Bed 3B faunal assemblage consists of 1,348 identifiable skeletal elements out of a total of slightly less than 2,000 specimens. An estimated minimum of fifty individuals representing a variety of mammals, a small number of birds and one reptile had become trapped or were killed when they fell into an open fissure leading into a small cave system. There is indication of the activity of carnivores and scavengers having modified some of the remains before they were completely buried by extraneous sediments. Several species of mammals in the deposit are identical with modern Tasmanian species. These include *Thylogale billardieri*, *Macropus rufogriseus*, *Potorous tridactylus*, *Mastacomys fuscus*, *Hydromys chrysogaster*, *Vombatus ursinus*, *Sarcophilus harrisii*, *Perameles gunnii* and an otariid belonging to the genus *Neophoca*. A large tachyglossid has been assigned to the living genus *Zaglossus*. Several species of extinct megafauna are also present. These include *Sthenurus occidentalis*, *Protemnodon anak*, *Macropus titan*, *Palorchestes*, *?Zygomaturus* and *Thylacoleo carnifex*. *Sthenurus occidentalis* is especially well represented.

In Tasmania, *Sthenurus occidentalis* is far more common than the eastern Australian species *Sthenurus orientalis*. The birds present include emu, and a rallid (*?Tribonyx*). The fauna suggests that at the time the Montagu area was more open than at present, with local dense scrub associations. A seasonally wet substrate is indicated. Grassland was present but not extensive. Evidence from the fauna and the Bed 3B sediments suggests that the environment was cold and wet at the time the animals lived.

Three strata of cave sediments consist of 1) a water born fine sediment having a soil horizon; 2) a frost fractured dolomite containing little matrix; and 3) a cave fill containing fauna and dolomite fragments reflecting some solution activity. These indicate substantial changes over time in the depositional environment at Montagu. The fine sediments in Bed 1 may have been deposited at the beginning of the Last Glacial phase. Deposition of Bed 2 probably reflects a cold, dry phase following an interstadial suggested by the cave soil developed on Bed 1. A subsequent cold wetter phase led to the deposition of Bed 3. Dating of bone collagen by the ^{14}C method suggests that the fauna in Bed 3B lived at the end of the Pleistocene, possibly as late as 10,000 years ago. This implies that Bed 2 deposition reflects the late Last Glacial phase of maximum cold (approx. 20,000 B.P.).

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Mr. Charles Turner identified dominant tree species in the surrounding forest and Thomas A. Darragh of the National Museum of Victoria identified a fossil marine pectinid preserved in a detrital rock fragment.

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APPENDIX

SPECIES	CHAMBER B (MU-206)	CHAMBER A (MU-206)	MAIN CAVE (MU-201)	MU-203	FLOWERY GULLY	SCOTCHTOWN	MOWBRAY SWAMP	PULBEENA SWAMP	BEGINNERS LUCK**	KING I	FLINDERS I	CAPE BARREN I	PASSAGE I	PRESERVATION I	E. KANGAROO I	DEAL I	ERITH I	THREE HUMMOCK I
AVES	X	X				X	X	X	X	X	X	X	X	X	X	X	X	
REPTILIA			X			X				X	X	X		X	X	X	X	
Tachyglossus				X	X	X				X	X							
*Zaglossus**	X		X			X				X								
*Macropus titan**	X					X												
Macropus giganteus	?		X	X	X											?		
Macropus rufogriseus	X	X	X	X	X	1	4		X	X	X	X		X		X	X	
Thylogale billardieri	X	X	X	X	X			X	X	X	X	X	X		X	X	X	X
Potorous tridactylus	X	X	X		X						X	X				X		X
Bettongia cuniculus					X													
*Protemnodon anak**	X					X				X								
*Sthenurus occidentalis**	X		X			X	3		X	X								
*Palorchestes azeal**	X	X				X	X	X										
*?Nototherium**						X	X			X								
*Zygomaturus**	?						X			X								
*Diprotodon**										X								
Trichosurus vulpecula					X								X			X	X	
Pseudocheirus convolutor			X		X					X	X	X						
Cercartetus nanus					X													
*Thylacoleo carnifex**	X					X												
Vombatus ursinus	X	X	X	X	X	X	5		X	X	X	X				X		
*Phascolonus**							X											
Isoodon obesulus					X						X	X	X					X
Perameles gunnii	X		X		X	X			X									
Antechinus spp.					X					X	?			?		?		
Sminthopsis					X													
Dasyurus viverrinus					X				X						?			
Dasyurus maculatus				X	X				X	X	X	X						
Thylacinus cynocephalus	X				X	X												
Sarcophilus harrisii	X				X	X					X							
Mastacomys fuscus	X				X				X									
Pseudomys higginsi					X		2		X	X								
Rattus lutreolus					X					X	X	X	X	X		X	X	
Hydromys chrysogaster	X																	
CHIROPTERA					X													
PINNEPEDIA (Neophoca sp.)	X																	

MONTAGU NW TAS S TAS BASS STRAIT ISLANDS

FOSSIL LOCALITIES

1. Listed as "wallaby" in Gill and Banks (1956)
2. Listed as "rodent" in Gill and Banks (1956)
3. Listed as "kangaroo" in Gill and Banks (1956) identified as either *Procoptodon* or *Sthenurus*, see p. 23 (ibid.)
4. Confusion arises here as to what is meant by "wallaby". Gill and Banks (1956: 23) suggest that this is *Macropus rufogriseus*
5. *Vombatus* was actually not recovered from the swamp deposit, but from a nearby cave (ibid. p. 23)

* Extinct, or as in the case of *Zaglossus*, extinct in Tasmania and Australian mainland

** Recently discovered fossil cave in the Florentine Valley, Southern Tasmania

(1977)
PROC. 11th BIENNIAL CONFERENCE
AUSTRALIAN SPELEOLOGICAL FEDERATION
CANBERRA, 1976

CAVES AND ABORIGINAL MAN IN TASMANIA

3

ALBERT GOEDE*

Abstract

The survival of archaeological evidence in Tasmania owes much to the suitable preservational environment found in shelter caves and, to a much lesser extent, in limestone caves. Cave art is almost unknown although hand stencils have been recorded. Recent work suggests that they may be the work of mainland aborigines. Extensive excavations of ancient sea caves at Rocky Cape have revealed an occupation history of some 8,000 years, while excavation of Cave Bay Cave on Hunter Island has yielded an archaeological record dating back nearly 23,000 years. Archaeological evidence from limestone caves is also increasing. In 1975, following the exploration of Beginners Luck Cave, investigations of bone deposits led to the discovery of an underground archaeological site. Dating of charcoal from the site has provided the first clear evidence of the presence of Aboriginal Man in the interior of Tasmania during the last ice age.

The survival of archaeological evidence in Tasmania owes much to the suitable preservational environment found in shelter caves and to a much lesser extent in limestone caves.

Cave painting was not characteristic of the Tasmanian aborigines although there are some historical references indicating that they painted on bark (Stockton 1976). The only cave art recorded consists of a number of hand impressions outlined in red ochre and found in two sandstone shelters in the Derwent Valley near Hamilton. The first shelter was reported by De Teliga and Bryden (1958) and has since been flooded by the Hydro-Electric Commission's Meadowbank Dam water storage. A second shelter in the same area (Meg's Mit Rock Shelter) has been reported recently by Stockton (1975, 1976) who states that "the paintings consist of three clear but faded hands stencilled in red ochre and several indecipherable lines in yellow, while on other parts of the walls of the cave red ochre marks are found, mostly in the form of irregular blobs". Examination of some three hundred other rock shelters in the area adjacent to the site has yielded no recognisable paintings although in some cases blobs of red ochre were found adhering to the walls.

The hand stencils appear to be identical to those found throughout mainland Australia. Jim Stockton has suggested that the stencils may be of post-European contact origin as a group of aborigines were brought from the Sydney area in the 1830's and used in an attempt to hunt down and capture the local natives. Hand stencils are prolific in sandstone caves in the Sydney region. It is quite feasible that Meg's Mit Rock Shelter was used as a camp by the mainland visitors as they are known to have spent some time in the general area.

The Rocky Cape Caves are ancient raised sea caves eroded in Precambrian quartzites. Several of them contain stratified archaeological deposits and two caves on the eastern side of the cape – North Cave and South Cave – have been excavated by Rhys Jones in 1964-65 (Jones 1968, 1971, 1975). He found that in both caves some three metres of midden deposit had accumulated. Aboriginal occupation began about 8000 years ago as the rising postglacial sea began to approach its present level. In North Cave at least, intermittent occupation continued until the time of European settlement. In South Cave progressive infilling gave rise to a room problem and the cave was abandoned about 3,500 years ago.

In early 1967 three children were exploring in South Cave when they discovered an additional chamber ('The Enclosed Chamber'). This enclosed chamber preserves a 'living floor' which was last occupied about 6,700 years ago after which time access was effectively prevented by the growing accumulation of shells in front of the entrance. The floor of the chamber revealed a number of small circular hearths, heaps of discarded shell, pieces of rock, bones and human faeces. Even some fragments of vegetable material had survived. Under the sloping roof, in a crevice at one end of the chamber, two pounding stones were found – one still in position on top of the other. The walls and roof of the chamber were stained by smoke and soot. The discovery was a highly significant one and caused considerable excitement at the time.

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The 8,000 years of archaeological record at Rocky Cape has yielded evidence of interesting changes in the nature of the coastal economy of the area. According to Jones (1975) it saw "the slow but steady attrition of the importance of seal which declined from contributing 95% down to 45% of the non-shellfish meat at opposite ends of the sequence, and the sudden disappearance of fish from the diet 3,500 years ago, a situation which persisted into historical times and for which only a cultural reason can be given".

Bone tools are found throughout the earlier part of the sequence but for unknown reasons their use was abandoned about 3,500 years ago. The sequence of stone implements shows an increasing emphasis on the use of exotic materials for the manufacture of tools – some of the raw material having come from as far as 80 km away from the site.

Of outstanding significance in recognizing the antiquity of Man in Tasmania has been the excavation of Cave Bay Cave on Hunter Island off the north-west coast of the state by Sandra Bowdler of the Australian National University (Bowdler 1974a,b, 1975).

The main period of Pleistocene occupation of Cave Bay Cave was between 23,000 and 18,000 years ago with an isolated hearth dated at 15,500 years BP. During this time the last Ice Age was still in full swing and sea level was much lower than it is today. Hunter Island was not then an island but connected to Tasmania which itself had a land connection with the Australian mainland. At that time the site would have looked out across extensive plains instead of the waters of Bass Strait as it does today.

After the island had been cut off by the rising sea it was still visited by the aborigines from time to time using bark canoes. Holocene shell middens which overlie the older Pleistocene deposits have been dated at approximately 2,500, 4,000 and 7,000 years ago (Bowdler, pers comm).

The Pleistocene deposits have yielded significant amounts of bone materials – both mammals and birds are represented. Well made and beautifully finished bone points have also been recovered. Some of the mammals recorded from the deposits are no longer present on Hunter Island but are still found on the Tasmanian mainland to the south. None of the bones belong to extinct species despite the considerable age of the lower layers of the deposit. This is all the more curious since a non-archaeological cave bone site, recently excavated by Peter Murray and the author near Montagu in northwestern Tasmania, has yielded remains of no less than six extinct species (Murray and Goede, in press). The site appears to be significantly younger than the basal deposits at the Cave Bay Cave site on the evidence available so far. This raises interesting questions about the relationships between early Man and many extinct Pleistocene marsupials (Jones 1968).

Another reason for the importance of the Cave Bay Cave site is that it is the first cave in Tasmania from which a pollen stratigraphy has been obtained (Hope, pers comm). This has given valuable information about the vegetation at the time when early Man was living in the area.

Archaeological evidence from limestone caves is limited but increasing. Gill (1968) recorded a bone implement from a cave fill, exposed in a limestone quarry at Flowery Gully. Unfortunately no stratigraphic information on this site has been recorded. Carbon 14 dating of the deposit was carried out on a mixed sample of bone and charcoal and suggested an age of some 7,000 years. However, bone is a notoriously unreliable material for carbon 14 dating and often yields a date significantly younger than the true age.

In 1975, following the exploration of Beginners Luck Cave in the Florentine Valley, investigations of bone deposits by Peter Murray and the author have led to the discovery of an underground archaeological site (Goede and Murray, in press). Finds included one probable bone point and four stone artifacts (Plates 1 and 2) associated with charcoal and charred bone fragments as well as spirally fractured and butcher-marked bones. The bone material identified belongs to eight species of mammals and two of birds. Figure 1 shows an interpretation of the evolutionary sequence of cave development and depositional phases that appears to have occurred at the site.

Carbon 14 dating of the associated charcoal has provided a date of 12,600 $\pm$ 200 years. This is the first clear evidence of the presence of Aboriginal Man in the interior of Tasmania during the last ice age. The find is of considerable significance since it had been widely believed that during late glacial times the interior of Tasmania was inhospitable and probably uninhabited (Jones 1968, Davies 1974).

Recent evidence from pollen profiles (Macphail 1975) indicates that Tasmanian vegetation in late glacial times was much more open than it is today. It now appears that the broad valleys of the interior of Southern Tasmania were much more accessible to Man at that time than they have been ever since and probably contained a more varied fauna. The present day natural vegetation of the Florentine Valley is a dense wet sclerophyll forest poor in animal life. There is no evidence that the area was visited by the aborigines at any time during the Holocene. Late Pleistocene excursions

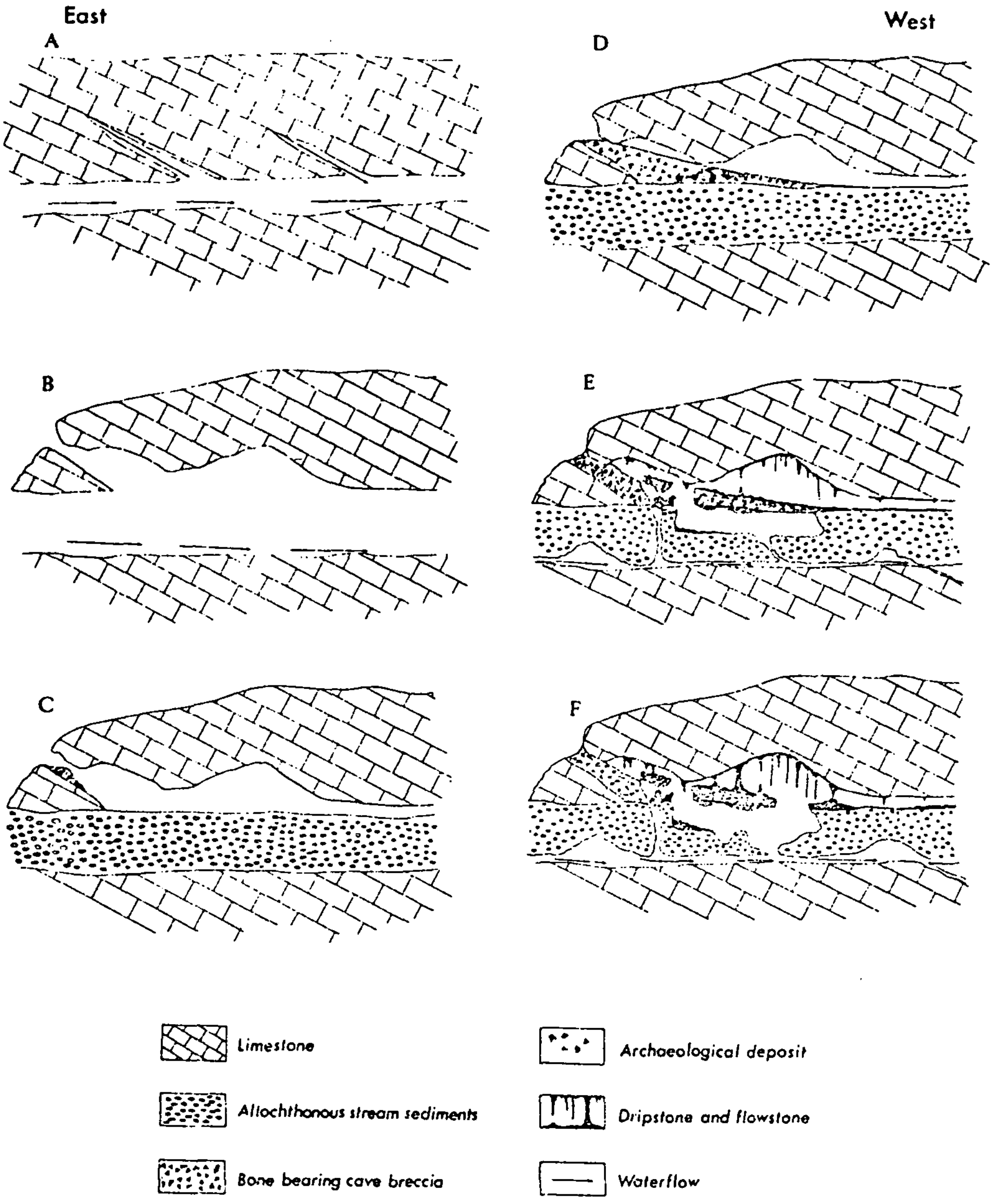

Fig. 1. An interpretation of the evolutionary sequence of cave development and depositional phases at site P, Beginners Luck Cave, Florentine Valley.

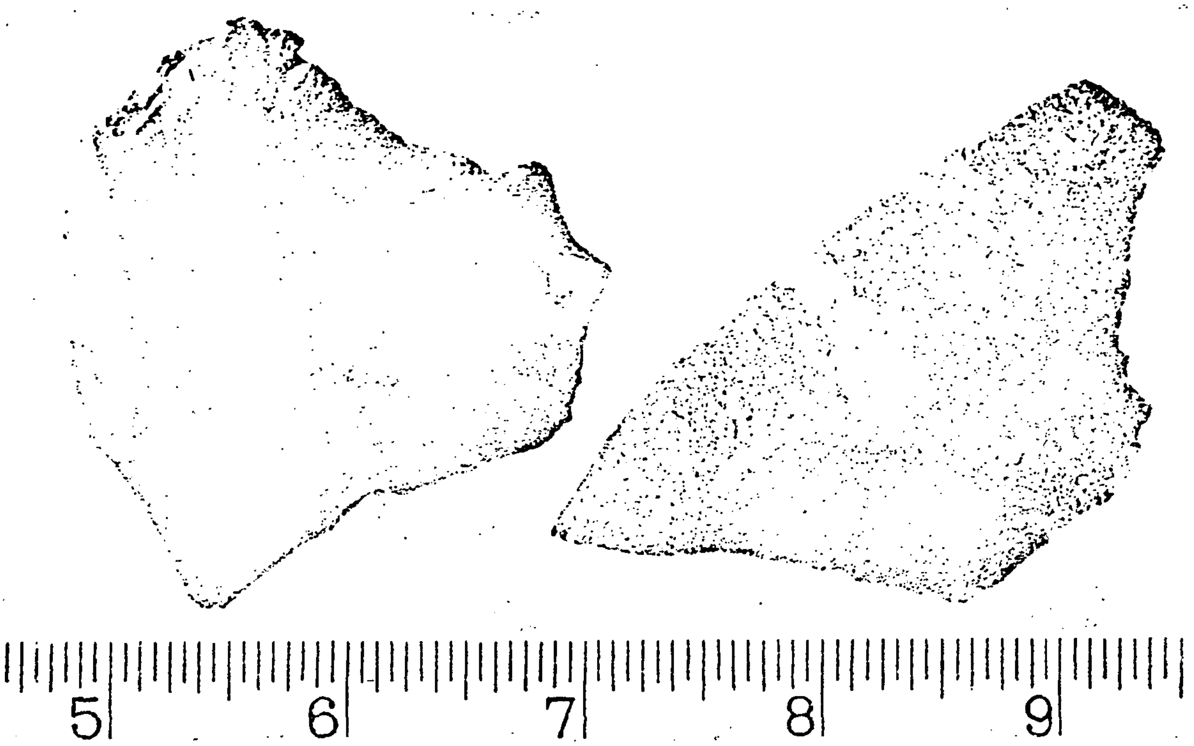

Plate 1

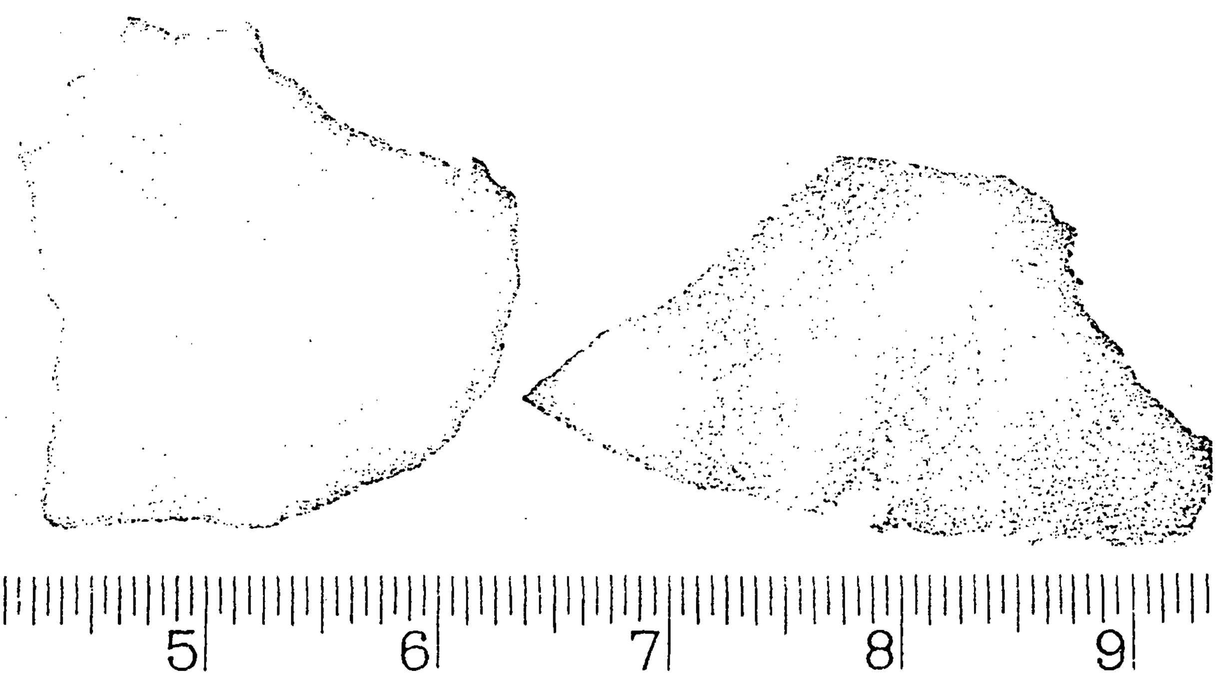

Plate 2

Plates 1 & 2. Two of the Pleistocene stone artifacts recovered from site P in Beginners Luck Cave, Florentine Valley.

inland were probably made by small hunting parties making use of spells of fine weather during the summer months.

A particularly interesting discovery supporting this idea was made when bird bones recovered from the Beginners Luck archaeological site were identified by Jerry van Tets of the CSIRO Division of Wildlife Research (Van Tets, in prep.). They included two bones belonging to the Sooty Shearwater *(Puffinus griseus)*, popularly known as a mutton bird. Van Tets believes that the most likely explanation for its presence is that it was picked up on the coast by Man and carried to the cave as food, or the bones may have been used as ornaments.

The discovery of the Beginners Luck site suggests the possibility that archaeological sites may be found in limestone caves in other inland areas in Western Tasmania despite the fact that such areas do not appear to have been occupied and exploited by Aboriginal Man since the Pleistocene.

Speleologists in Tasmania can be of considerable assistance in adding to our archaeological evidence from caves by reporting the presence of bones, charcoal and artifacts in cave deposits. However, such evidence should *never* be removed from a site by amateur cavers since the position of archaeological material within the deposit and the nature of the sediments surrounding such material can yield information of archaeological value.

Exploration of sea caves could also be very rewarding as it is becoming clear that most of our larger sea caves, whether active or abandoned, predate the last ice age. Many of them would have been located considerable distances inland during the times of low sea levels associated with cold climate conditions. Some would have provided suitable shelter for Aboriginal Man. Where sedimentary deposits are exposed in such caves they should be closely inspected for the presence of archaeological material.

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PLEISTOCENE MAN AND MEGAFAUNA IN TASMANIA: DATED EVIDENCE FROM CAVE SITES

ALBERT GOEDE*, PETER MURRAY+ and RUSSELL HARMON†

ABSTRACT

Cave deposits on south-central and north-western Tasmania (Figure 1) have yielded dated evidence of the survival of elements of late Pleistocene megafauna perhaps as recently as 11,000 years ago. In addition, archaeological sites from the two areas have provided evidence of the presence of Aboriginal man 20,000 years or more before the present. In Tasmania there was probably a period of some 10,000 years when Pleistocene man and megafauna co-existed. The near absence of extinct fauna from archaeological sites indicates that early man was not a big game hunter.

Extinction of many elements of the late Pleistocene fauna appears to have occurred between 16,000 and 11,000 years ago. The most likely cause was rapid vegetational change as a result of climatic warming, aided perhaps by low-frequency anthropogenic fire. As well, the populations of larger species may have fallen below critical minimum levels as a result of the flooding of Bass Strait.

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MS received: 27 April, 1978.

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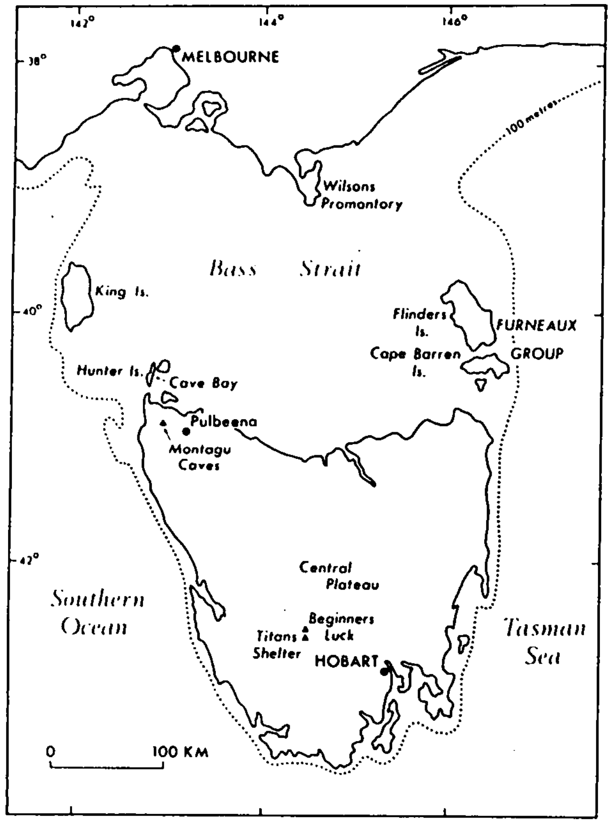
Figure 1: Locality map of sites discussed in this paper.



INTRODUCTION

Cave sites in the Florentine Valley and near Montagu have been studied by the authors. A. Goede has detailed the geomorphological and stratigraphic evidence, while P. Murray has examined the palaeontological and archaeological content. R. Harmon is responsible for the Th/U dating of speleothems from one of the sites.[1]

The localities discussed are sites P and M in Beginners Luck Cave (JF-79) and site G in Titans Shelter (JF-97), all of which are located in the Florentine Valley in south-central Tasmania (see Figure 1). Near Montagu, in the north-west of the state, evidence is presented from sites in Chambers A and B in Pleisto Scene Cave

(MU-206). Evidence is also quoted from the Cave Bay Cave site on Hunter Island excavated by Bowdler (1974a, 1974b, 1975).

FLORENTINE VALLEY SITES

Beginners Luck Cave, Site P

The archaeological evidence and bone content at this site have previously been described by Goede and Murray (1977), but since then further excavations have been carried out. The litho-stratigraphic sequence consists of two units. The lower unit is composed of alluvial gravels containing pebbles derived from a number of rock types. This unit is almost devoid of bone and contains no archaeological evidence. The upper unit is a limestone breccia representing an entrance facies deposit which reached its present position as a debris flow from a former entrance. This unit contains significant amounts of bone as well as archaeological material in the form of stone tools and worked bone. A radiocarbon date obtained on charcoal taken from throughout the unit yielded an already published date of 12,600 ±200 B.P. (Goede and Murray 1977). As pointed out in that paper, the sample was not pre-treated for carbonate contamination and the date therefore represents a minimum age.

Since then, excavation of a 1 metre square test pit has revealed that the upper unit can be sub-divided into three sub-units (2A, 2B and 2C, from bottom to top). Archaeological material is largely confined to the 2B layer, from which a number of additional artifacts were recovered. Charcoal from sub-unit 2B was C14 dated at 20,650±1,790 B.P. (GaK-7081) after treatment with HCl and NaOH to remove any possible contamination by more recent carbon. The date indicates significantly earlier human occupation than previously thought. The slightly less than 1000 bone fragments from sub-unit 2B have been assigned to *Mastacomys fuscus* (minimum number of individuals = 16); *Macropus rufogriseus* (7 individuals); *Thylogale billardieri* (2 individuals); *Macropus* cf. *titan* (identification based on a cuboid); *Perameles* sp. (1 individual); and *Dasyurus viverrinus* (1 individual). Fifteen longbone fragments are burned, and a macropod humerus bears a pair of fine transverse cuts interpreted as marks made with a stone tool. With one exception, all of these bones belong to species still found in Tasmania at present.

Beginners Luck Cave, Site M

Information on this site has previously been published (Goede and Murray 1977). The site, in another part of the cave, consists of a scatter of bones belonging to an extinct browsing kangaroo (*Sthenurus* sp.) found on the surface of a muddy slope. There is no evidence of any association with man. Goede and Murray (1977) state that "A radiocarbon date on the organic carbon residue of the bone yielded an age 14,450±250 B.P. (R 5001/3)....Any C14 date on bone should be treated with caution as such material is readily contaminated by younger organic acids contained in seepage water at any time since its deposition." The fact that the bone was never buried by subsequent sedimentation may have reduced the risk in this case.

Titans Shelter, Site G

The site is located in the second chamber of a steeply inward-sloping limestone shelter cave located some 1.5 kms SSW of Beginners Luck Cave. The bottom of this chamber has been eroded below the original level of late Pleistocene cave fill, and within its sloping floor was a circular erosion pit. The bone-rich cave fill exposed in the walls of the pit was excavated to form a flat-floored rectangular excavation of 75 x 120 cms with a depth varying from 75 to 95 cms due to the slope of the floor.

Except for a thin unconsolidated mantle of Holocene sediments, dated on charcoal to 1140±90 B.P. (GaK-6874), the sequence consists of a bright brown stony cave earth rich in small bone fragments. The condition of these fragments indicates that the material has originated from a carnivore's den (probably *Sarcophilus*). The nature of the sediments indicates re-deposition by slow-moving water in the form of a fan with intermittent roof fall contributing to the sediments.

Charcoal collected from a depth of 58-75 cms from the downslope (southeastern) wall of the excavation was pretreated with HCl to remove carbonate contamination before C14 analysis. The sample yielded a date of $14,310^{+2970}_{-2160}$ B.P. (GaK-6875). While this date appears to be much younger than that obtained from the main human occupation layer (Bed 2B) at Site P (20,650±1,790 B.P.), the standard errors of both dates are large (the small amounts of dateable material available at both sites limited the sample sizes). It is nevertheless probable that the fauna at Site G is slightly younger than that in Bed 2B, Site P. The important point however is that it is unlikely to be older.

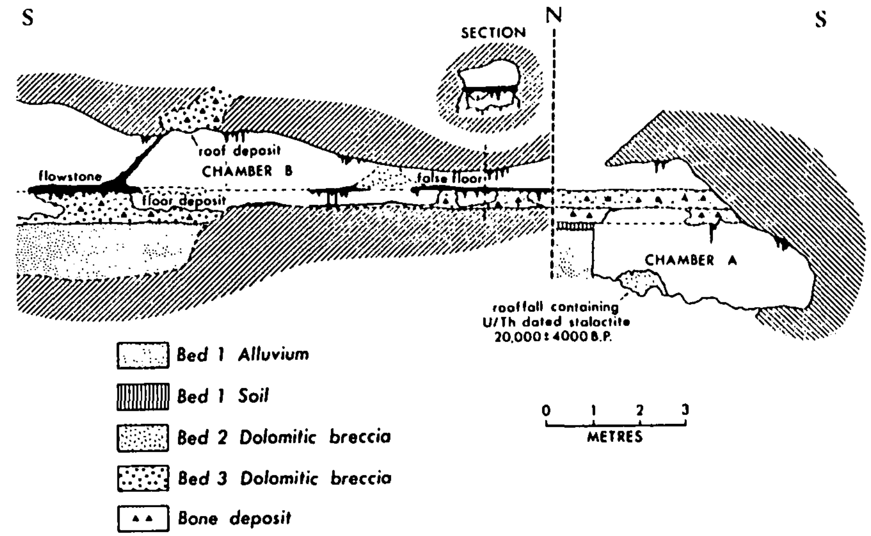
The site has yielded the following extinct fauna, which occurs throughout the pre-Holocene sediments: *Macropus titan*, *Protemnodon anak*, *Sthenurus* sp., *Sarcophilus* cf. *laniarius*, and an unidentified diprotodontid, probably *Zygomaturus*.

NORTH-WESTERN SITES

Pleiso Scene Cave, Chambers A and B

The stratigraphic sequence of sediments from this cave and the vertebrate remains from Bed 3 in Chamber B have been described in Murray and Goede (1977). The stratigraphic relationships are summarized in Figure 2. A brief summary of the site and its

Figure 2: Diagrammatic drawing of stratigraphy of Pleisto Scene Cave, Montagu. Chamber A has its long axis reversed to show more clearly the stratigraphic relationships of its sediments with those found in Chamber B.



contents is given, and the likely age of the Bed 3 fauna is discussed.

The late Pleistocene deposits exposed consist of three super-imposed sedimentary units, best seen in Chamber A. The oldest unit (Bed 1) consists of at least 1.5 metres of clay-rich, fine-grained alluvial sediments varying from yellowish brown to reddish brown in colour and containing sporadic small bone fragments. The upper 40 cms of the unit appears to represent a fossil soil, which indicates that a period of stability occurred prior to the deposition of Bed 2.

Bed 2 consists of a strongly cemented breccia up to 50 cms thick, with numerous angular dolomite fragments. These range in size from 10 centimetres down to a few millimetres in diameter, and clearly were derived by a physical weathering process, almost certainly frost action. The material varies from having an open framework to containing a sparse fine-grained matrix. The sediment has a significant bone content, but this has not been examined in detail because the nature of the outcrop makes excavation difficult.

Bed 3 is also a dolomitic breccia, with a minimum thickness of one metre in Chamber A. Cementation is highly variable, but it is mostly strongly cemented. The dolomite fragments are coarser, with a general range of 1 to 10 cms; a few blocks are up to 40 cms in diameter. There is an abundant fine-grained matrix. The sub-angular nature of the rock fragments suggests derivation by physical weathering followed by some solutional rounding prior to deposition. Beds 2 and 3 represent detritus derived from cave entrances by frost and transported by solifluction processes to form sloping sheets and debris fans.

Excavations have taken place in Chamber B only 10 metres distant from Chamber A. The stratigraphy is similar except that Bed 2 is absent, with Bed 3 directly overlying Bed 1. Bed 3 is present in the form of a debris fan, the material having entered through the roof by means of a former entrance. Excavation of this deposit has yielded a rich fauna, including a number of extinct species. Murray and Goede (1977) report the presence of *Sthenurus* sp., *Protemnodon anak*, *Macropus titan*, *Zaglossus robusta*, *Thylacoleo carnifex*, *Palorchestes* sp. and ?*Zygomaturus*.

Because the mandibular fragment and two teeth representing *Zygomaturus* and *Palorchestes* were extracted from the matrix in the laboratory it is possible, although not likely, that they came from the contact surface between Beds 1 and 3 and may therefore predate the deposition of Bed 3. The presence of the remaining five extinct species in Bed 3, however, is firmly established.

The age of Bed 3 is difficult to determine with precision. Murray and Goede (1977) have presented two bone collagen dates which can only be regarded as minimum age determinations. An age of not less than 10,000 B.P. is indicated.

The maximum age is limited by a U/Th age determination on a detrital stalactite fragment incorporated in Bed 2 in Chamber A. This yielded an age of 20,000±4,000 B.P., the large standard deviation being due to the relatively low uranium content of the specimen. The stalactite clearly predates most if not all of the deposition of Bed 2 sediments which in turn predate Bed 3. It is therefore unlikely that the age of Bed 3 sediments is greater than 20,000 years B.P.

Murray and Goede (1977) have argued that Bed 2 accumulated under conditions of maximum cold during the Last Glaciation, and that a reduction in mean winter temperatures of 8°C was necessary in order to produce physical weathering by frost. Work by Colhoun (1975) at Henty Bridge has indicated that the maximum extent of Last Glaciation ice in western Tasmania was not attained until about or slightly after 20,000 B.P.

Bed 3 appears to have accumulated under somewhat less extreme conditions. Slight solution rounding of many dolomite fragments prior to final deposition suggests a period between the

depositional phases of Beds 2 and 3 of little physical weathering, possibly wetter conditions and stable surface soil mantles. This was followed by renewed soil instability leading to the deposition of Bed 3. The more abundant matrix compared with Bed 2 may reflect wetter conditions of deposition. Less extreme cold climate conditions at the surface may be indicated by the fact that physical weathering was not so pronounced.

Beds 2 and 3 can only have accumulated in the absence of forest vegetation, and at least a partially bare ground surface seems likely. Present day evidence from disturbed sites in the Tasmanian mountains clearly indicates that frost-induced weathering and mass movement are restricted by the presence of a vegetation cover rather than by limiting values of temperature. It is therefore pertinent to examine available evidence on the vegetation history of the region.

Colhoun, Mook, and van de Geer (n.d.) have examined the pollen content of peats and marls at Pulbeena Swamp, 20 kms to the east of the Montagu caves. The sediments at this site appear to have preserved a continuous record of vegetation changes for approximately the last 140,000 years, the last 50,000 of which have been dated by C14 methods. Interpretation of the pollen profile indicates cold, dry conditions from approximately 25,000 to 11,000 B.P., with an open vegetation dominated by grassland. Around 11,000 years ago there was a rapid change to warm moist conditions, which lead to the development of tall open *Eucalyptus* forest (that remained dominant in the area until historical times).

Conditions for the accumulation of cave breccias of the type found in Beds 2 and 3 appear to have been favourable during the period 25,000-11,000 B.P., with accumulation of Bed 2 possibly representing the glacial maximum not long after 20,000 B.P. The age of Bed 3 is most likely within the range 16,000-11,000 B.P.

Aboriginal occupation in north-western Tasmania was recently shown to extend back more than 22,000 years when Bowdler (1975) obtained a date of 22,750±420 B.P. (ANU-1498) from an archaeological deposit at Cave Bay Cave on Hunter Island. With the low sea levels prevailing at that time Hunter Island would have been an integral part of the Tasmanian mainland (Bowdler 1974b). The site is located 38 kms NNW of Pleisto Scene Cave. Human occupation at Cave Bay Cave is documented by the presence of bone and stone tools, and a considerable amount of bone that has been interpreted as human food refuse. The largest animal represented in the deposit is a wallaby. Remains of extinct Pleistocene megafauna such as recorded from Titans Shelter and Pleisto Scene Cave are not present in Cave Bay Cave.

CONCLUSIONS

Evidence from the sites discussed leaves little doubt that there was a considerable period of time, perhaps as long as 10,000 years, when early man and now extinct species of megafauna co-existed within the Tasmanian region. Jones (1968) has argued that man's arrival in Australia may have been the decisive factor in the extinction of many of the larger forms of the late Pleistocene fauna. However, the two Tasmanian Pleistocene archaeological sites that have been dated so far seem to indicate that while early Aboriginal man was certainly a hunter, he appears to have concentrated on taking medium to small marsupial species. The evidence accumulated from sites in mainland Australia in recent years points in a similar direction (Bowdler 1977).

A number of species of now extinct late Pleistocene Tasmanian fauna not only survived the arrival of man but also the period of maximum cold (20,000-15,000 B.P.) of the last glaciation. They are *Macropus titan*, *Protemnodon anak*, *Sthenurus* sp., *Sarcophilus laniarius*, *Thylacoleo carnifex*, *Zaglossus robusta* and at least one species of Diprotodontidae.

It appears highly unlikely that extinction of these species is due to either human predation or to excessively cold or dry conditions during the glacial maximum. A much more likely cause is the rapid vegetational change which occurred about 11,000 years ago and is now well documented (Colhoun 1978; Macphail 1975). This rapid change is primarily due to the climatic transition from glacial to post-glacial conditions, but may very well have been accentuated by the effect of anthropogenic fires. In Tasmania, open vegetation was favoured in late Pleistocene times by low temperatures rather than by high fire frequency judging by the paucity of charcoal in most deposits of this age. Pollen diagrams indicate that climatic change towards the end of the Pleistocene was towards wetter and warmer conditions which favoured forest growth (Colhoun, Mook, and van de Geer n.d.). But, man was on the scene, and probably used fire in an attempt to keep the country open. This may have been effective in retarding the spread of rainforest, but it would have encouraged the growth of eucalypt forest by destroying the existing ecosystem and creating favourable micro-climatic and edaphic conditions for the regeneration of eucalypts. Some species of *Eucalyptus* would already have been present in the environment in the form of mallee-type shrubbery. Under climatic conditions trending towards those prevailing at present, early man in the wetter areas of Tasmania could have maintained open vegetation only through a very high frequency of fires (Jackson 1968). A recurrence interval of less than 50 years would be required, and in failing to achieve such a high frequency he would unwittingly have aided the conversion from open vegetation to sclerophyll forest. Colhoun *et al.* (n.d.) referring to the Pulbeena pollen site located 20 kms east of the Montagu caves, state that "around 11,000 years B.P. there was a rapid change to warm moist conditions leading to the development of tall open *Eucalyptus* forest which has remained dominant in the area until historical times."

Probably at some time between 12,000 and 13,000 B.P. the rising sea level isolated Tasmania from the Australian mainland (Jennings 1971). If some of the species with which we are concerned were still present on the Australian mainland at that time, isolation of a small Tasmanian population and a reduction of territory may have hastened the decline and extinction of the larger species. However, Hope (1977) has reviewed the dated faunal sites on the Australian mainland, and suggests that the crucial date for the disappearance of extinct genera may be about 15,000 B.P. and that only smaller forms, and/or those occurring in coastal regions, survived to that time.

If this can be further substantiated it would indicate that Tasmania, prior tp its isolation, was already a refuge for relict populations of late Pleistocene fauna.

NOTES

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We are grateful to Dr. John Haight and Denis Charlesworth who assisted with the excavations, and Mr. Guus van de Geer who drew the figures. The manuscript was typed by Terese Flannagan.

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APPENDIX: ANALYTICAL METHODS USED IN $^{230}Th/^{234}U$ DATING OF STALACTITE FROM CHAMBER A, PLEISTO SCENE CAVE, MONTAGU

The isotope activity ratio, U concentration, and calculated age were determined at Michigan State University following a procedure slightly modified from that described by Thompson (1973) A sample of about 100 grams of speleothem calcite was dissolved in cold 2N HNO_3 and filtered if any insoluble detrital material was present. A $^{232}U/^{228}Th$ tracer and an Fe^{3+} carrier were then added to the solution and allowed to equilibrate before coprecipitation of the radioelements with $Fe(OH)_3$ was induced by the addition of 200 ml NH_4OH. After washing with distilled, deionized water, the precipitate was dissolved in 50 ml 9N HCl and radiochemically pure U and Th separated by anion exchange on Dowex 1X-8 resin in the chloride and nitrate form respectively. Further purification was accomplished by organic solvent separation before the U and Th sample was plated onto a stainless steel disc for radioactive counting. ^{230}Th, ^{232}Th, ^{234}U and ^{238}U activities were measured by alpha spectrometry using the $^{232}U/^{228}Th$ tracer to monitor yields.

The reported age was calculated from the measured $^{230}Th/^{234}U$ activity ratios assuming that: (1) all observed ^{230}Th activity was produced *in situ*, and (2) there was negligible ^{230}Th activity in the speleothem from detrital material included in the speleothem material at the time of deposition. The high $^{230}Th/^{232}U$ ratios support this latter assumption. We are confident of the age because: (1) none of the sample was recrystallized from aragonite to calcite or showed significant evidence of post-depositional alteration, and (2) the speleothem age is in correct stratigraphic order. The U concentration is low and therefore the standard error of the date is fairly large.

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(ms. received 4.12.1978)

LATE PLEISTOCENE BONE DEPOSITS FROM A CAVE IN THE FLORENTINE VALLEY, TASMANIA

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(with six text figures, one table and five plates)

ABSTRACT

GOEDE, A. and MURRAY, P., 1979 (20 vii): Late Pleistocene bone deposits from a cave in the Florentine Valley, Tasmania. *Pap. Proc. R. Soc. Tasm.*, 113: 39-52 (incl. five plates). ISSN 0080-4703. Department of Geography, University of Tasmania, Hobart, Tasmania and Tasmanian Museum and Art Gallery, Hobart, Tasmania, Australia.

A limestone shelter cave in the Florentine Valley, south-central Tasmania, has yielded vertebrate remains. Two of the three sites excavated have yielded evidence of the presence of elements of the Pleistocene megafauna. The morphology and stratigraphy of the cave is described. Pleistocene deposits are shown to consist of two units. A lower unit laid down by water with an admixture of roof fall and an upper unit of angular limestone detritus derived from physical weathering within the cave entrance. C-14 dating indicates a late Pleistocene age for material collected from one of the sites. Its stratigraphic relationship to the other sites is discussed.

INTRODUCTION

Palaeontological and geomorphological investigations were carried out in Titans Shelter, a limestone shelter cave, in 1976 and 1977. It is located just below the crest of a limestone hill at an elevation of 400 m within the broad valley of the Florentine River some 23 km north-northwest of Maydena (146°28'9"E, 42°34'57"S). It is approximately 1.4 km south-southwest of Beginners Luck Cave where the authors have previously investigated a Pleistocene archaeological bone site (Goede and Murray, 1977) (figure 1).

Excavations were made at three sites (E, F and G) and all have yielded vertebrate remains (figure 2). Site G proved the most rewarding containing a number of extinct species which included *Macropus titan*, *Protemnodon* sp., *Sthenurus* sp., *Sarcophilus* sp. and an unidentified diprotodontid. The bones at this site have been extensively chewed and fragmented suggesting derivation from a carnivore's den - probably occupied by *Sarcophilus*. The small passage from which the material entered the chamber is at present inhabited by *Sarcophilus harrissii* as evidenced by fresh coprolites found during some of our visits.

CAVE DESCRIPTION

The cave has developed in well-bedded Ordovician limestone (Gordon Limestone) locally dipping south-west at an angle of some 25°. The cave is shown in plan in figure 2 and in longitudinal section in figure 3. The cave mouth is situated in a steep anti-dip slope close to the crest of the hill and consists of a wide, low opening (5 x 2.2 m) facing north-east (plates 1 and 2). The cave floor slopes steeply inwards at a maximum angle of 35° from the crest of a natural rampart approximately three metres outside the roof line of the entrance. The roof of the entrance chamber looks unstable and descends in a series of steps formed by roof fall parallel to the bedding. Despite the unstable appearance of the roof there has been little recent roof fall as evidenced by joint-aligned rows of spongy stalactitic formations covered by algal growth.

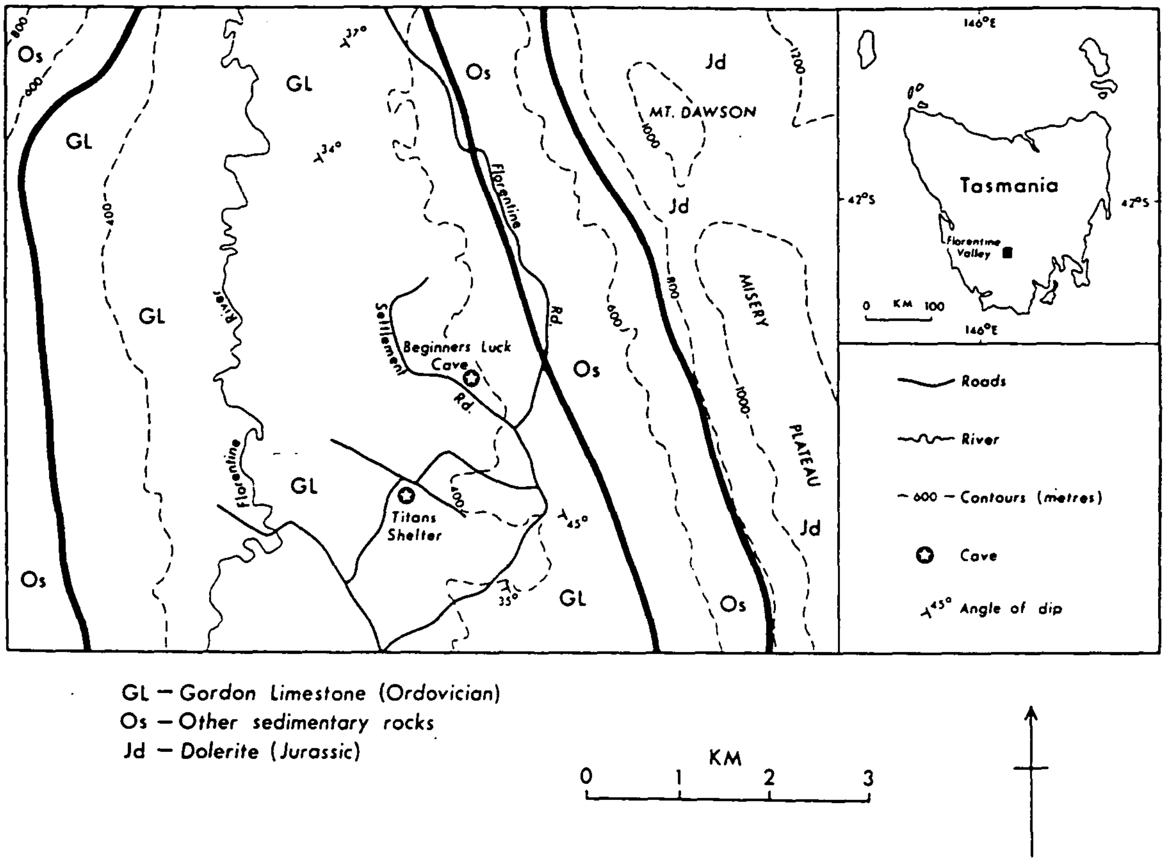

FIG. 1.- Locality and lithological map of part of the Florentine Valley (lithology after Corbett 1963).

The floor is partly covered by slabs of roof fall - the largest being 2.0 x 2.3 x 0.35 m. These are partly imbedded in a dull yellowish brown (10 YR/4/3) (Standard Soil Color Chart 1965) cave earth mixed with an abundance of smaller limestone fragments and containing significant amounts of charcoal and organic matter. Much of the surface charcoal was derived from burning of slash in the summer of 1975-76 following clearfelling.

The entrance chamber has maximum dimensions of 8 x 9 m with a maximum ceiling height of 2.3 m. Along the south-western wall approximately 40 cm below the ceiling a wide, low-roofed extension slopes downward at an angle of 20° becoming too tight for human penetration after about three metres. It has a bedrock ceiling and a floor consisting of clastic sediments.

At the lowest point of the entrance chamber the roof steps down to a point where large roof fall originally blocked further access. A small opening against the south-western wall was enlarged to provide entry to a second chamber.

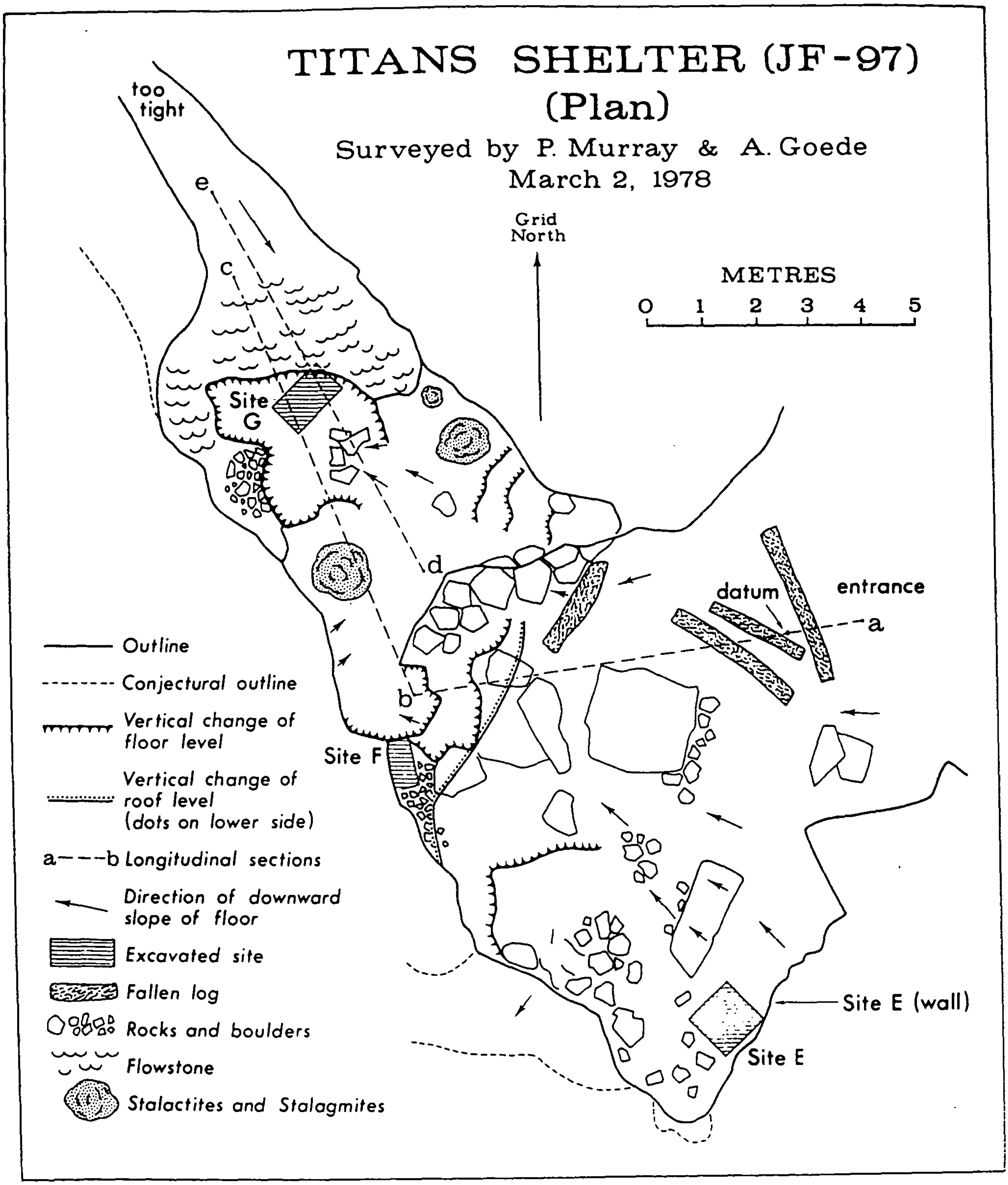

FIG. 2.- Plan survey of Titans Shelter.

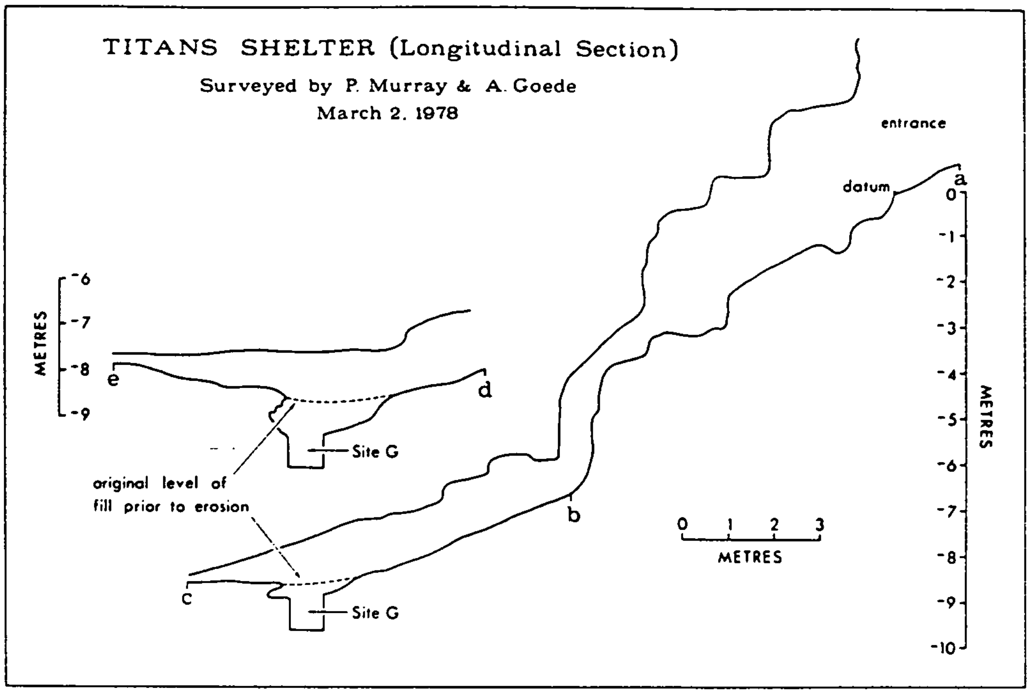

FIG. 3.- Longitudinal section of Titans Shelter.

This chamber is six metres long and up to five metres wide with the floor sloping towards a low point near the north-western extremity. Here, prior to excavation of site G, a circular pit approximately one metre deep and with a maximum diameter of 60 cm had been eroded in the dissected cave fill making up the floor.

At the north-western extremity of the chamber the floor rises again and a flow-stone covered slope leads to a low tunnel which soon becomes too tight to allow further exploration. A draught is present possibly indicating another connection with the surface.

EXCAVATION SITES AND ASSOCIATED SEDIMENTS

Three sites were excavated within the cave, two in the entrance chamber and one in the second chamber.

Site E was located below the south-eastern wall of the entrance chamber (figure 2). In the lower wall above the level of the pit and a little to the north-east some bones and bone fragments were exposed in remnant cave fill containing abundant angular limestone fragments. In the upper 20 cm there is a sparse dull yellowish brown (10 YR/5/4) matrix while the lower 20 cm has an openwork texture. The rock fragments generally range from a few mm to 10 cm in diameter with a modal range of 2-4 cm. Occasional larger fragments up to 30 cm are present. This site is referred to as Site E (wall) in figure 2. Site E was selected because of its proximity to this wall exposure and also because it was one of the few areas in the entrance chamber where large blocks of limestone were absent from the surface. Excavation of a one metre square area on this sloping site revealed a thin uncompacted surface layer of dull

PLATE 1 (top).- View of limestone hill with entrance to Titans Shelter visible below crest.
PLATE 2.- Entrance to Titans Shelter.
PLATE 3 (bottom).- Seiving for bone fragments outside the cave entrance.

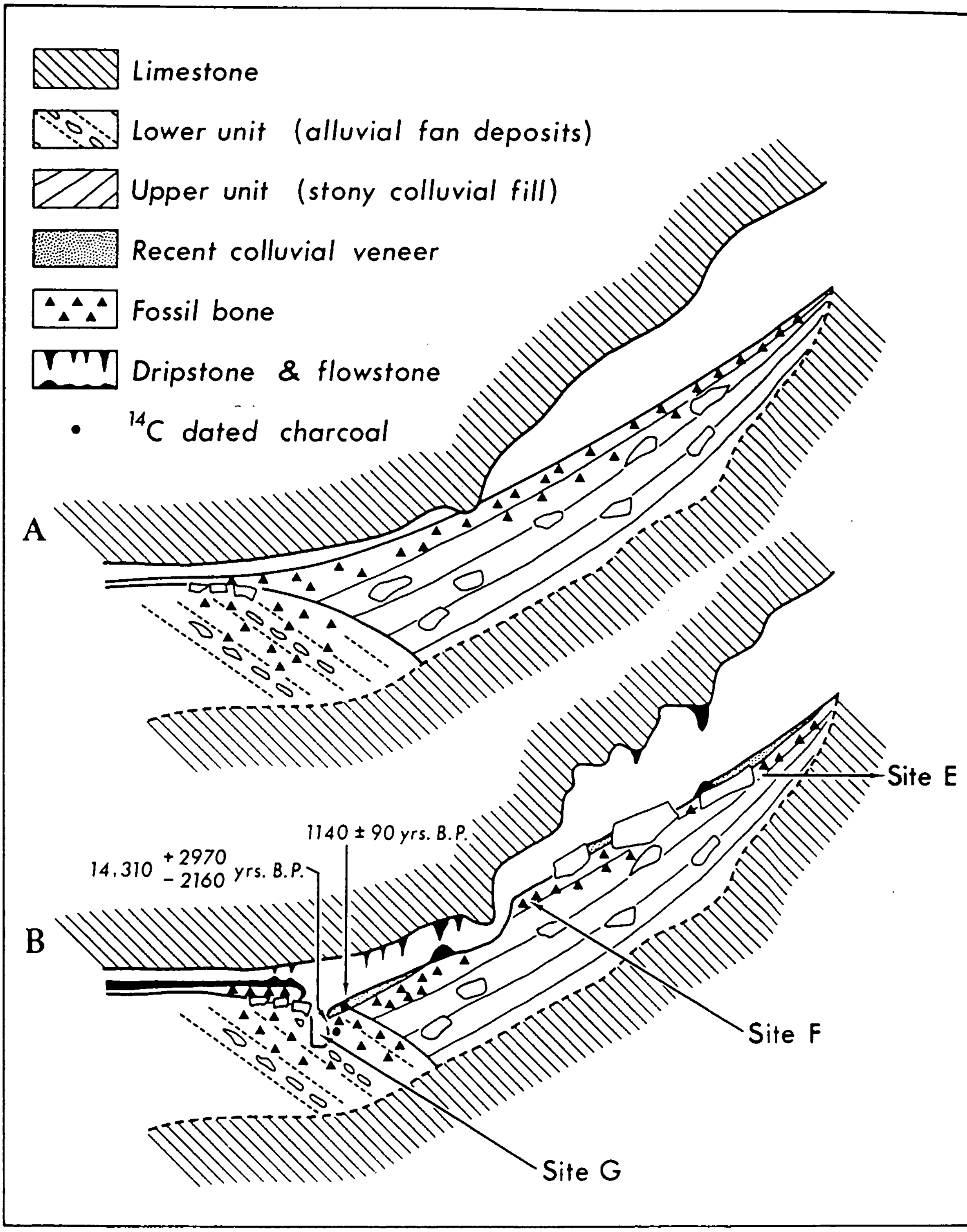

FIG. 4.- Diagrammatic evolutionary sequence of depositional and erosional phases. A, end of Pleistocene. B, present day.

yellowish brown (10 YR/5/3) stony earth thickening downslope and locally containing numerous small bones. There was a steeply dipping contact with marked erosional unconformity between it and the underlying sediments. These sediments form a continuous sediment body with the E wall sediments but are stratigraphically lower in the sequence. They consist of a loosely packed rock rubble in a partial matrix of bright brown (7.5 YR/5/6) earth. Voids are common and there is abundant evidence of subsequent deposition of spongy calcium carbonate by percolating water. The stone size tends to increase towards the base of the exposure with many fragments from 5 to 20 cm in diameter.

The sediments contained a number of bone fragments, many of them broken. A single fragment of angular grey quartzite was also discovered (dimensions 49.0 x 56.5 mm). This represents the only piece of non-limestone rock found so far in any of the sediments examined in this cave. Although it is tempting to suggest that it was brought to the cave by man it shows no clear evidence of being an artifact. Excavation of site E was abandoned because of the decreasing bone content with depth and increasing problems with large blocks of roof fall.

Site F consists of a remnant of undissected cave fill preserved against the west wall of the entrance chamber near its lowest point (figures 2 and 4). The deposit consists of an accumulation of limestone fragments ranging in size from angular chips a few mm in diameter to fragments up to 15 cm. The modal size range is approximately 1 to 3 cm. In the upper part of the deposit the fragments are contained in a sparse matrix of reddish brown (5 YR/4/6) clay rich sediment but downwards this grades into an openwork accumulation of angular rock fragments frequently coated with spongy calcium carbonate. The exposure shows at least one metre of sediments of which the top 40 cm are rich in fossil bone and have been excavated. Cementation of the deposit is quite variable ranging from strongly cemented to loose and friable.

Site G is located at the lowest point of the cave and has been briefly described in an earlier paper (Goede, Murray and Harmon 1978). Prior to excavation it consisted of a circular erosion pit approximately one metre deep and with a maximum diameter of 60 cm. The exposure of numerous small bone fragments in the sides of the pit prompted selection of the site for excavation. The pit was itself located in the floor of a larger erosional depression the outline of which is clearly shown in figure 2 as a vertical change in floor level. The sedimentary sequence is partially capped by flowstone deposition from water entering the chamber from the north-west (figures 2 and 4).

The upper unit of the underlying sediments is up to 70 cm thick and is best exposed to the west of the site and above the level at which excavation started. The deposit is strongly cemented and consists of limestone fragments from a few mm to 30 cm in diameter with a modal size range from 2 to 10 cm. There is a sparse matrix of poorly-sorted, dull yellow orange (10 YR/6/4) sediments containing significant amounts of fragmented bone. There is an erosional gap at floor level which separates it from the lower unit exposed in the pit.

To the north of the pit the upper unit rests on the lower one but the two are separated by a layer of limestone slabs approximately 30 cm thick produced by roof fall. The upper unit is poorly exposed here due partly to heavy post depositional incrustation of carbonate and partly to subsequent excavation of animal burrows below the flowstone cap. There appears to be a higher proportion of matrix, yellowish brown (10 YR/5/6) in colour, and also containing bone fragments.

The overall slope of the surface of the upper unit indicates that the sediments originated from the present entrance. This unit represents the last major phase of clastic deposition in the cave and the sediments are similar to those exposed at sites E and F with which they are correlated. The erosional depression around site G has been excavated largely within the upper unit, the material having apparently been removed through the erosional gap between it and the lower unit.

The lower unit consists of at least 90 cm of brown to bright brown (7.5 YR/4/6 to 5/6) cave earth with a significantly lower stone content than the upper unit. This material was originally exposed in the walls of the pit which was excavated to form a flat-floored rectangular excavation with dimensions of 75 x 120 cm and with depth varying from 75 to 95 cm due to the slope of the floor. The deposit is rich in small bone fragments in a state of preservation varying from very good to soft and crumbly. The nature of the bone fragments, to be discussed later, indicates that the material originated from a carnivore's den (probably *Sarcophilus*).

The sediments show poorly developed bedding dipping towards the south-east with apparent angles of dip of 25°-35°. A similar depositional slope is indicated by a roof fall horizon. In contrast to the overlying bed the sediments have been derived from the constricted passage entering the chamber from the north-west. Their nature indicates deposition by slow moving water in the form of a fan with intermittent roof fall contributing. The sediments are locally penetrated by modern roots several of which had to be cut during excavation.

Charcoal collected from the deposit from the south-eastern wall of the excavation at a depth of between 58 and 75 cm below the surface was carefully inspected for possible modern root contamination and pretreated prior to dating with boiling 2N HCl solution. The age was determined as $14{,}310 \begin{smallmatrix} + 2970 \\ - 2160 \end{smallmatrix}$ years BP (GaK-6875).

The sections (figure 4) show that on the north-western side of the pit the older sediments are overlain by a low mound of much more recent reddish brown (5 YR/4/6) sediment which accumulated as a result of animal burrowing (probably by *Vombatus ursinus*) in the upper unit. This is clearly a recent event postdating the dissection of the upper unit.

On the south-eastern side of the pit the sediments of the lower unit are overlain by a thin (< 10 cm) layer of loose charcoal rich sediment which accumulated as a thin mantle after dissection of the older deposits. Charcoal from this layer was pretreated with boiling 2N HCl solution and yielded a late Holocene date of 1140 ± 90 years BP (GaK-6874).

FAUNAL ANALYSIS

Samples of fossil vertebrate remains were recovered from three sites in Titans Shelter. Site E yielded insufficient material for statistical analysis. Sites F and G both contained numerous whole and fragmentary bones in sufficient quantity to permit comparison with other Florentine Valley cave deposits.

Site E: A clear faunal demarcation between Holocene and Pleistocene sediments was apparent in this test excavation. The upper, probably mid to Late Holocene stratum contains only small mammal remains which represent regurgitated predatory bird pellets. The marsupial mouse *(Antechinus swainsoni)* and the long-tailed rat *(Pseudomys higginsi)* are the dominant elements in the deposit. A single canine of a Peramelid (probably *Perameles*) was also recovered.

The lower brown stratum contained *Thylogale billardieri*, *Macropus rufogriseus* and *Dasyurus viverrinus*.

Site F: A total of 659 specimens of fossil bone was excavated from a small area of less than .5m^2 excavated to an average depth of 25 cm. About two-thirds of these remains were identifiable to genus. Nearly 10 per cent of the sample was composed of unbroken long bones (plate 4).

The material shows evidence of both pre and post depositional alterations by predators and rodents. Tooth marks attributable to marsupial carnivores appear on four per cent of the specimens (figure 5). Eroded compact bone surfaces suggest that some of the fragments may have passed through the digestive system of a carnivorous animal. These comprise another four per cent of the sample. Six per cent of the remains consist of small fragments of long bones that appear to be the result of chewing. In addition, a few bones (1%) have paired, narrow grooves running perpendicular to the long axis of the bone or crests on bones. These grooves closely approximate the dimensions of the occlusal surfaces of *Mastacomys fuscus* incisors.

PLATE 4.- Sample of bone material collected from Site F.

The broken bone fragments in site F fall primarily into four shape categories: oblique (27%) transverse (35%) longitudinal fractures (27.5%) and spiral fractures (3%). The longitudinal fractures appear to be the result of natural weathering processes. Experiments by Miller (1975) suggest that freezing, thawing and drying of fresh bone results in longitudinal cracks that extend into the medullary cavity. Many of the transverse cracks also appear to be due to postmortem exposure to extremes of atmospheric conditions. Oblique and spiral fractures probably occurred while the bone was relatively fresh. The presence of collagen in the bone facilitates this type of damage when shearing forces are applied or when a bone is struck solidly with a heavy object. In site F this could be due primarily to roof fall and secondarily to the activity of carnivores.

Site F contained seven mammal and one bird species (table 1). The remains of a falcon (*Falco* sp.) and the unusually large number of *Dasyurus viverrinus* remains (120 elements) suggest that owls employed the shelter as a roost. Nineteen very large macropodid elements have been assigned to *Macropus titan*. A single metatarsal IV of *Sthenurus* sp. was also recovered. *Macropus rufogriseus* is the most common species from site F, comprising 44% of identifiable remains. *Thylogale billardieri* and *Macropus titan* remains were less common (respectively 7% and 5%). *Sthenurus* is comparatively rare.

The overall representation of skeletal remains shows an expected predominance of axial elements (18%), poor representation of the cranium (3.1%) and good representation of mandibles (9.1%). Pes elements were greatly over represented in the sample (21%).

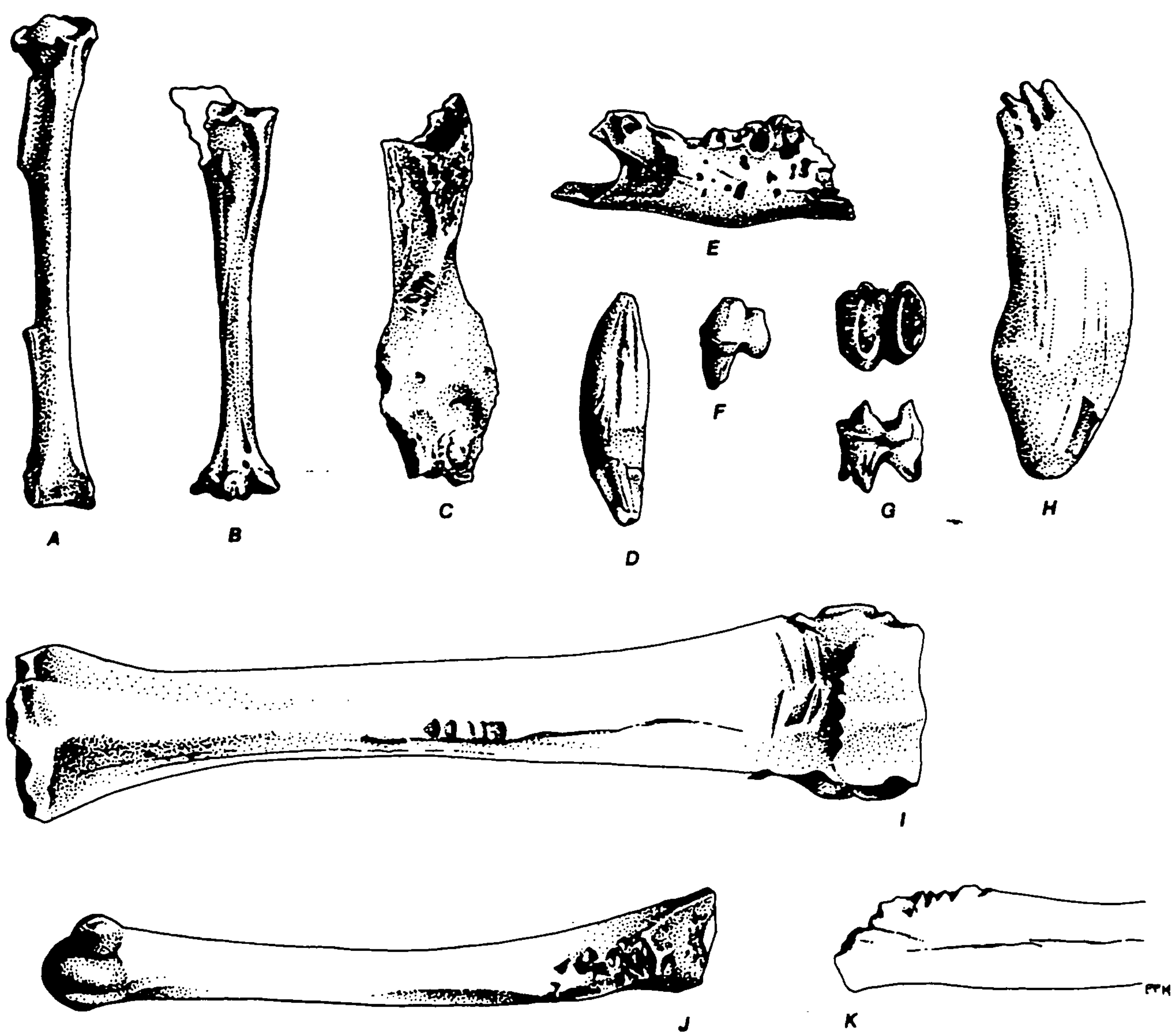

FIG. 5.- Drawing of selected fossil remains from sites F and G. A, tibiotarsus of *Falco* sp.; B, tarsometatarsus of *Falco* sp.; C, humerus of *Macropus rufogriseus* showing tooth marks and damage to distal and proximal ends by gnawing; E, mandible of *M. rufogriseus* showing attack by snails; D, upper left canine of *Sarcophilus* sp.; G, left M^3 of *Sthenurus* sp. (occlusal and buccal views); H, I^1 of *?Zygomaturus*; I, metatarsal IV of *Macropus titan* showing marks probably made by a carnivore near distal end and marks made by rodent(s) in the middle of the shaft; J, metatarsal V of *Macropus titan* showing tooth marks near proximal end; K, side view of same.
A, B, C, E, I, J, K; x 0.57.
D, F; x 0.7.
G x 0.86.
H x 0.65.

TABLE 1

SPECIES IDENTIFIED IN TITANS SHELTER

Species	Site F		Site G
	Minimum Number	Total Remains Identified	Minimum Number
Falco sp.	1	10	-
Dasyurus viverrinus	18	120	1
Sarcophilus sp.	-	-	4
Pseudocheirus peregrinus	-	-	2
Vombatus ursinus	-	-	1
Sthenurus	1	1	3
Protemnodon	-	-	2
Macropus titan	4	19	8
Thylogale billardieri	2	29	4
Macropus rufogriseus	5	178	5
?Zygomaturus	-	-	1
Mastacomys fuscus	5	44	4

Site G: This sample primarily consists of small, apparently chewed bone fragments averaging between 2 and 3 cm in length. The vast majority of these fragments are technically unidentifiable, although the limited faunal assemblage present in these sites would allow generic assignment on the basis of element size alone. Identification of species and estimates of minimum numbers of individuals are based entirely on isolated teeth and jaw fragments containing teeth (table 1).

Site G contains more species than Site F, but this is probably due to the much larger sample obtained from this location. The total number of fragments exceeds 5000. A representative sample of site G material consisting of 215 specimens was measured by placing each piece in one of seven two-centimetre categories. This was compared with the Site F sample (figure 6).

In site G the number of fragments in the size categories of between 8 and greater than 12 cm is practically nil. In site F there is at least a small representation in each of these larger categories (figure 6, plates 4 and 5). A χ^2 test suggests that the differences in size distribution of bone fragments at the two sites is highly significant ($\chi^2 = 50.13$, $v = 4$, $p < .001$).

The most likely explanation for the difference in size of fragments is that site G represents water sorted and transported material. It seems very likely that the initial assemblage of fossil material represented only in part at site G is a large deposit. Unfortunately, the passage leading to its probable source is too narrow to negotiate.

PALAEOECOLOGY

The modern Florentine Valley fauna consists of species known to inhabit wet sclerophyll and rainforest biomes throughout Tasmania. Samples of fauna from Late Holocene deposits in the valley contain the remains of *Ornithorhynchus*, *Tachyglossus*, *Antechinus swainsoni*, *Dasyurus maculatus*, *Sarcophilus harrisii*, *Thylacinus cynocephalus* (now presumed extinct), *Perameles gunnii*, *Vombatus ursinus*, *Potorous tridactylus*, *Thylogale billardieri*, *Macropus rufogriseus*, *Pseudocheirus peregrinus* and *Pseudomys higginsi*. Despite the relatively large samples of fossil material from sites F and G, a substantial number of these species are not represented. Important absences include the tiger cat *(D. maculatus)*, the marsupial mouse *(Antechinus swainsoni)*, the velvet

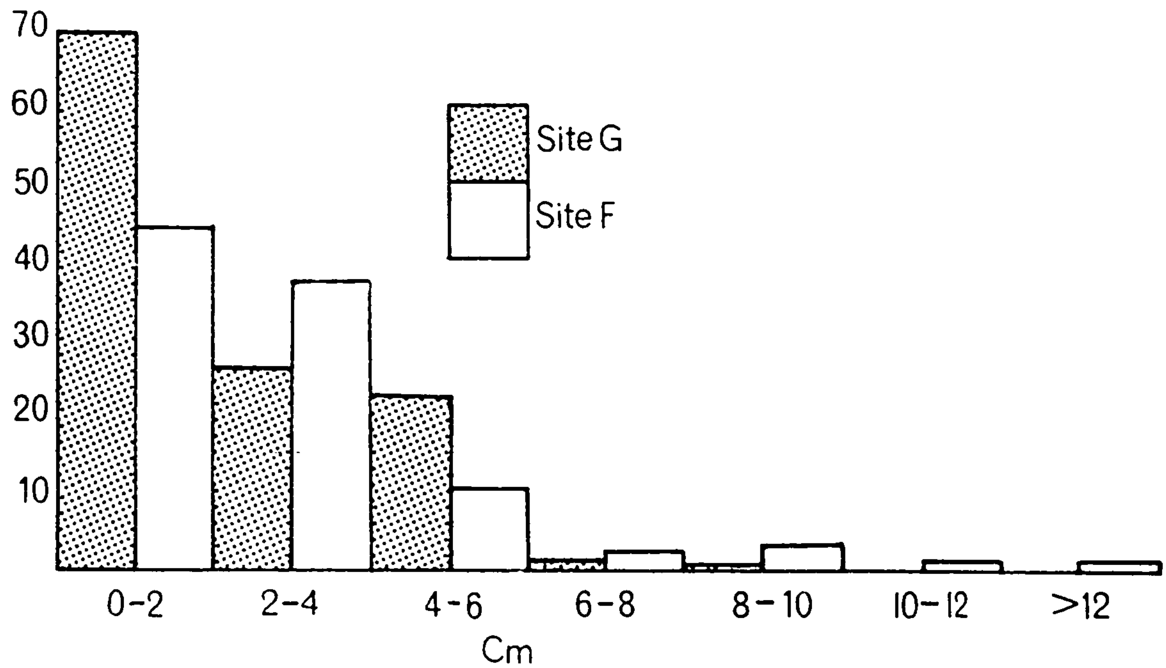

FIG. 6.- Size distribution of bone fragments for sites G (n = 215), and site F (n = 659).

PLATE 5.- Sample of bone material collected from Site G.

furred rat *(R. lutreolus)* and the potoroo *(Potorous tridactylus)*. These mammals are typical fern gully and rainforest edge species. However, certain constituents of the fossil fauna suggest the presence of some type of arborescent vegetation and/or scrub, particularly *Pseudocheirus*, *Sthenurus* and *Thylogale*. The large kangaroo, *M. titan* was probably similar to the modern grey kangaroo in preferring open sclerophyll and woodland savanna habitat. *Mastacomys fuscus* is a relict species in Tasmania. Its distribution during the Late Pleistocene was greatly expanded, while *Rattus lutreolus* and *Pseudomys* spp. appear to have been very rare. *M. fuscus* may have preferred open sedge and grassland habitats. It is today confined to cool, wet sedgeland and grassland associations. The Titan Shelter assemblage appears to represent an open vegetation type community consisting of some sclerophyll forest elements and some low scrub situated within grasslands.

HISTORY AND AGE OF SEDIMENTATION

The lower unit excavated at site G represents the oldest sediments exposed in the cave. The base is not exposed as it was not possible to deepen the excavation further without digging into collapse material at the base of the pre-existing erosion pit. Unlike the upper unit the provenance of the sediments is from the north-westerly trending passage that continues on from the second chamber. The nature and bedding of the material indicates accumulation by running water in a low energy environment contemporaneous with intermittent roof fall. A very short distance of transport is suggested by the nature of the bone content.

Extinct fauna is represented throughout the excavated depth. Charcoal is not common and at only one place occurred in sufficient quantity to permit C14 dating ($14{,}310\ ^{+2970}_{-2160}$ years BP). The large standard error is due to the small size of the sample. The date indicates a late Pleistocene age. This date has been quoted by Goede, Murray and Harmon (1978) as evidence of Late Pleistocene survival of megafauna in the Florentine Valley. However, it cannot be regarded as conclusive evidence. Since the bone content has been reworked the possibility exists that the bone is significantly older than the charcoal with which it is associated.

The upper unit is exposed in the banks above the level of excavation site G. The upper horizons of the same unit were examined at sites E (wall), E and F while some of the lower horizons are exposed in the squeeze below site F. Beds with limestone fragments in a sparse matrix alternate with layers of open work fragments. Both bone and matrix seem to be concentrated in the upper horizons but bone is relatively abundant only at site E.

The upper unit appears to have accumulated as a result of gravitational movement downslope of material produced by roof fall and physical weathering. The nature of this deposit suggests cold and probably dry conditions during its formation. It is similar in character to the upper unit described from site P in Beginners Luck Cave (Goede and Murray 1977) and the two deposits may be of similar age. The increase in the content of bone and matrix in the upper horizons may reflect a gradual moderation of climatic conditions.

Unfortunately the unit contains no significant amounts of charcoal that would enable it to be dated. There is no evidence of a significant time gap between the accumulation of the upper and lower units. The upper unit is believed to represent the final phase of Pleistocene deposition prior to the climatic warming which led to the invasion of forests at about 11,500 C14 years BP (Macphail 1975).

It is followed by a long period when erosion by seepage water and deposition of calcium carbonate were the dominant processes. Lack of physical weathering and widespread chemical deposition suggest mild and wet climatic conditions which may have persisted through much of the Holocene. Patchy cementation and local spongy carbonate deposition within the late Pleistocene fills probably also occurred during this time.

Following this episode there was very restricted clastic deposition in late Holocene times. This seems to have been due to the activities of birds and burrowing animals and also to occasional disturbance of the forested surface environment by fire. An episode of fire disturbance is dated at 1140 ± 90 years BP.

CONCLUSIONS

An unknown thickness of late Pleistocene deposits partially filled Titans Shelter and can be subdivided into two units. The lower unit was deposited by running water with an admixture of rockfall. The fragmentary bone content represents a late Pleistocene megafauna and suggests surface vegetation conditions rather different from the dense wet sclerophyll forest present in historical times. The C14 date obtained from the unit has been used by Goede, Murray and Harmon (1977) as evidence for the late survival of Pleistocene megafauna in Tasmania but the large standard error of the date combined with the possibility that the bone material may be older than the sediments in which it occurs must throw some doubt on the evidence.

The younger unit indicates cold and dry conditions with evidence of fauna indicated only in the upper horizons. Accumulation may have occurred under conditions of maximum cold during the last glaciation with some amelioration towards the end.

The balance then swung to a dominance of sediment removal by running water and speleothem formation during the wetter and milder conditions of the Holocene. The most recent events are minor erosion and sedimentation due to biological activity in the cave and fire disturbance of the surface environment.

ACKNOWLEDGEMENTS

We are grateful for the financial support received by one of us (A. Goede) from the Australian Research Grants Committee towards the cost of field work and C14 dating of the site. Assistance from the University of Tasmania and the Tasmanian Museum is also acknowledged.

We appreciate the help of Denis Charlesworth in the seiving operations on the site and the cleaning of bone material in the laboratory. Mrs. Kate Morris drafted the maps and diagrams and the manuscript was typed by Terese Flannagan.

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Postscript

Since this paper has gone to press the authors have received an aspartic acid racemization date on bone from Dr. J.L. Bada of the Scripps Institution of Oceanography, University of California, U.S.A. The dated bone fragment comes from site G and has a D/L aspartic acid ratio of .141 and an estimated age of ~ 40,000 years B.P. The age was calculated using $K_{asp} = 1.7 \times 10^{-6} yr^{-1}$, the estimated value at 8°C derived from the Cave Bay Cave (Hunter Island) K_{asp} value at 12°C. While only approximate it indicates a much greater age for the bone material than the C^{14} date on associated charcoal (see par.3, page 46).

The date supports the possibility suggested by the authors that the lower unit bone material may be significantly older than the sediments in which it occurs (see par.2, p.51 and par.1, p.52).

A. Goede

PALAEOCLIMATIC INFORMATION FROM CAVES

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Abstract

Palaeoclimatic information can be obtained from caves by analysing the oxygen isotope composition of calcite and aragonite deposited as stalagmites.

A palaeotemperature record is useful only if it can be dated. In the last decade considerable progress has been made in the radiometric dating of speleothems by means of the uranium-thorium method. Material from 2 000 to 300 000 years old can be dated by this method.

Two oxygen isotopes ^{16}O and ^{18}O are used in palaeotemperature work. In nature there are small natural variations in the ratio between the two ($^{18}O/^{16}O$) and the value of the ratio is temperature dependent. The values can be measured by means of a stable isotope mass spectrometer and are expressed as parts per thousand ($^{o}/_{oo}$), and designated as $\delta^{18}O$. Measurements are made on sealed samples of carbon dioxide gas prepared from calcium carbonate.

If closely spaced samples are taken from a longitudinal section of a stalagmite and the value of $\delta^{18}O$ determined for each sample a curve of temperature change against time can be plotted if the age of different layers within the stalagmites can also be determined.

Tasmania, the south-east of Australia and the south-west of Western Australia offer considerable scope for this field of research.

INTRODUCTION

Palaeoclimatic information is of interest because of Man's increasing concern about the possibility of rapid climatic change in the perhaps not too distant future. Either a swing to significantly warmer conditions or to significantly cooler conditions could spell disaster for our present day civilization.

Warmer conditions would cause melting of the Greenland and Antarctic icecaps resulting in wholesale inundation of coastal plains. Colder conditions would severely restrict agriculture and would cover large areas of land with glacial ice.

The climate is changing at present and a major concern is to assess the relative extent to which man-made and natural factors are responsible. Natural factors tend to be cyclic in nature and if we have available to us an accurately dated record of past temperature change we can start to predict future changes due to natural factors. Then, by comparing them with actual changes we may ultimately assess the influence of Man on our changing climate (Calder, 1974).

Such records can be obtained from oxygen isotope analysis of the ice sheets of Greenland and Antarctica, from deep sea cores and from speleothems in caves.

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The most suitable for palaeotemperature work are stalagmites because they are characterised by slow vertical growth and show distinct growth layers which can be sampled when the stalagmite is cut lengthwise (Plate 1).

RADIOMETRIC DATING

No palaeotemperature record is useful unless it can be dated. During the last ten years reliable Uranium/Thorium dating has become available (Harmon, Thompson, Schwarcz & Ford, 1975; Gascoyne, Schwarcz & Ford, 1978). Most stalagmites contain minute amounts of uranium including ^{234}U which decays to ^{230}Th with a half-life of 247 000 years. The development of α particle spectrometry has made possible analytical measurements of very small quantities of radio-active isotopes. The U/Th method of dating can be used over a time period of 2 000 to 300 000 years BP - a time range which is covered by very few other dating methods.

For a stalagmite to be dated it must have:

(1) A U content of not less than 0.1 ppm. Uranium content can be determined quickly and cheaply by delayed neutron analysis by the Australian Atomic Energy Commission in Sydney.

(2) An absence of clays and a very low content of other detrital minerals (< 0.5%), otherwise the specimen must be rejected. The ratio $^{230}Th/^{232}Th$ is determined during the dating procedure. It gives an indication of the degree of detrital contamination. If the ratio is < 20 the sample is once again rejected.

(3) Absence of any evidence of post-depositional recrystallisation.

OXYGEN ISOTOPES

The element oxygen has three stable isotopes, ^{16}O, ^{17}O and ^{18}O. The two that concern us in palaeotemperature work are ^{16}O and ^{18}O. Oxygen 16 is by far the most abundant being approximately 500 times more common than ^{18}O. However, in nature there are small variations in the ratio ($^{18}O/^{16}O$) and these can be used to gain information on palaeotemperatures (Bowen, 1966; Hendy & Wilson, 1968; Hendy, 1969; Harmon, Thompson, Schwarcz & Ford, 1978).

METHOD OF MEASUREMENT

Measurement of the ratio is by means of a stable isotope mass spectrometer. It is made on CO_2 gas and is calculated as follows:

$$\delta\ ^{18}O\ ‰ = \left[\frac{(^{18}O/^{16}O)\mathrm{SAMPLE} - (^{18}O/^{16}O)\mathrm{STANDARD}}{(^{18}O/^{16}O)\mathrm{STANDARD}}\right] \times 1000$$

Measurements are made in this way because the mass spectrometer can measure differences between two samples much more accurately than the actual value for one sample. The procedure eliminates any systematic measurement errors. The ratio is multiplied by 1000 to avoid dealing with small fractions of numbers. The standard most often used is SMOW and is approximately equal to the mean isotopic composition of ocean water.

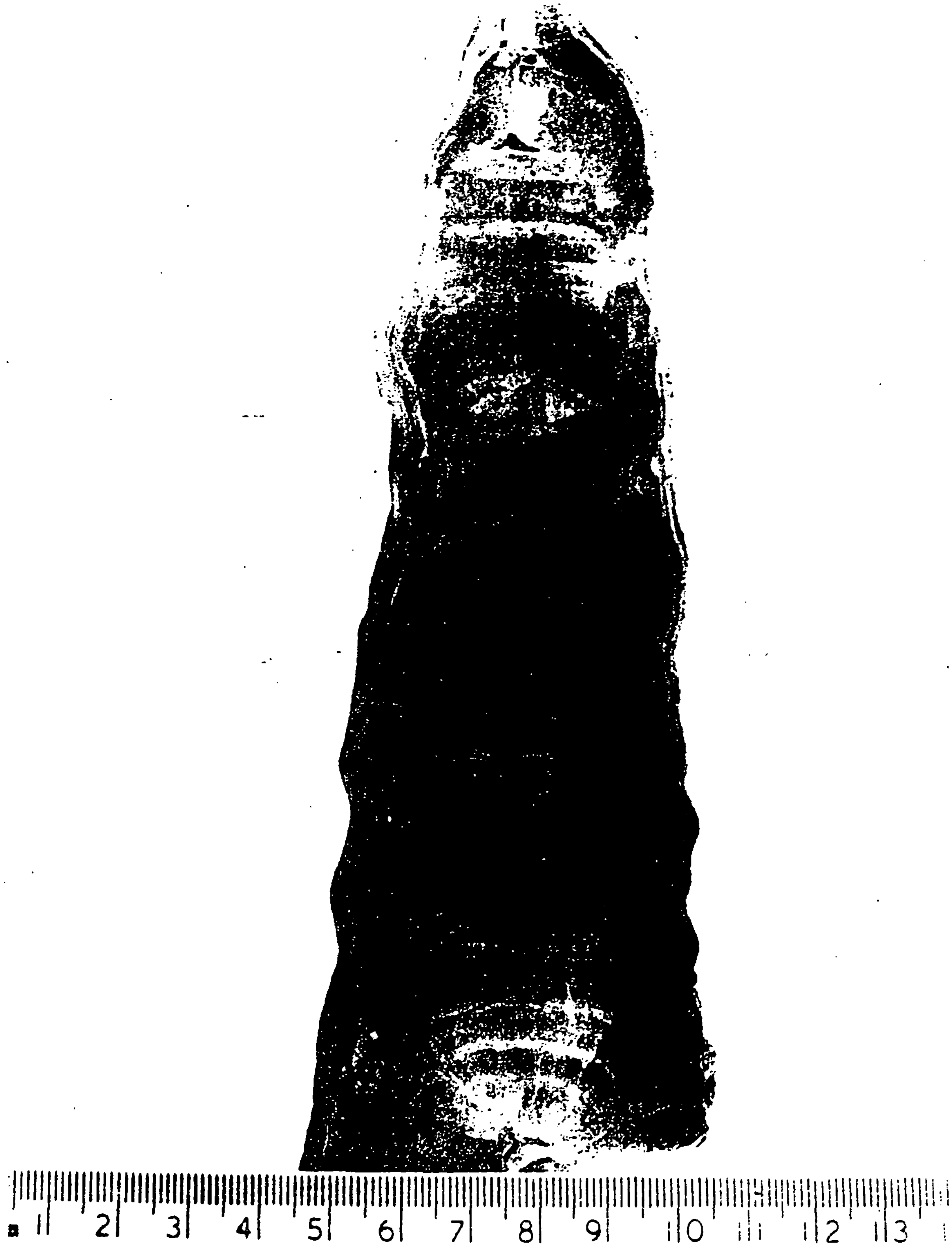

Plate 1. A small stalagmite showing internal structure, from King George V Cave, Hastings, Tasmania.

The substances on which $\delta^{18}O$ is usually determined are H_2O (water, ice) and calcium carbonate (calcite, aragonite). The range of variation of $\delta^{18}O$ found in nature is shown in Table 1 for a number of sites.

Table 1

Variations of $\delta^{18}O$ found in nature

Material analysed	Location	Range of values ($\delta^{18}O$)		Standard
SEASONAL VARIATIONS		*summer*	*winter*	
precipitation	Virginia, U.S.A.	-1.0	-14.0	SMOW
cave drips	Virginia, U.S.A.	-4.5	-7.9	SMOW
precipitation	Thule, NW Greenland	-17	-40	SMOW
CLIMATIC VARIATIONS		*interglacial*	*glacial*	
stalagmite	North Island, N.Z.	-4.0	-2.5	PDB
stalagmite	Virginia, U.S.A.	-6.1	-4.6	PDB
glacial ice	Thule, NW Greenland	-25	-43	SMOW
foraminifera skeletons (*G. sacculifera*) from deep sea core	Equatorial Pacific Core V28-238	-2.2	-1.0	B1

FRACTIONATION

The reason why oxygen isotope ratios can give an indication of palaeotemperature is due to the natural occurrence of fractionation.

Fractionation occurs when one isotope is transferred preferentially in one of two situations of interest to us. One such case is where there is a change of state (for example, from liquid to gas) and the other where a substance containing oxygen crystallises from an aqueous solution. Three situations are relevant:

1. Ice volume effect. When there is a change of state, water vapour evaporated from the surface of the ocean (or any other body of water) contains a higher proportion of the lighter isotope ^{16}O than the original water body.

During glacial phases large amounts of water are withdrawn from the oceans and incorporated into continental ice sheets. It causes ^{18}O enrichment of ocean waters during glacial times of the order of $1.1°/_{oo}$ during full glacial conditions.

2. Temperature effects. Fractionation not only occurs during evaporation of water but also during condensation and freezing. The degree of fractionation taking place is temperature dependent. Evaporation and condensation at lower temperatures produce lower values of $\delta^{18}O$ in precipitation (sometimes called the precipitation effect). It means a depression of $\delta^{18}O$ values of precipitation in glacial times. It also means that for the earth as a whole $\delta^{18}O$ values in precipitation tend to decrease towards the poles and increase towards the equator (latitudinal effect).

Outside the equatorial zone there is also a marked seasonal variation with higher values of $\delta^{18}O$ in summer precipitation and lower values in winter precipitation (seasonal effect). Seasonal temperature effects are variable in time and space (Dansgaard, 1964). For six continental sites in the U.S.A. they were found to vary from + 0.17 to + 0.39 $\delta^{18}O$ $^{\circ}/_{oo}$ $^{\circ}C^{-1}$ (Harmon, Schwarcz & Ford, 1978).

These variations cannot be used to estimate the temperature effects during a glacial-interglacial cycle because the seasonal effect would be affected by the temperature of evaporation at the source area as well as at the site of condensation and precipitation.

In addition both latitudinal and seasonal effects differ from the glacial-interglacial temperature effect because the latter is also influenced by the ice volume effect which tends to reduce the magnitude of the temperature effect. For West Virginia, U.S.A. Harmon, Schwarcz & Ford (1978) estimate the glacial-interglacial temperature effect to be + 0.14 $^{\circ}/_{oo}$ $^{\circ}C^{-1}$.

3. Crystallisation effect. When a substance containing oxygen crystallises from a saturated solution of water or where calcite or aragonite is extracted from water by biochemical means, fractionation also occurs. The calcite or aragonite is slightly enriched in ^{18}O in relation to the water from which it crystallises and the degree of enrichment is temperature dependent. Bowen (1966) states:

Temperature	Ratio in parent solution	Ratio in $CaCO_3$
0°C	1:500	1.026:500
25°C	1:500	1.022:500

This means that for water of constant isotopic composition, $\delta^{18}O_c$ (the $\delta^{18}O$ value of calcium carbonate) will be inversely related to the temperature at which it formed. We can call this the crystallisation effect and its magnitude is -0.24 $^{\circ}/_{oo}$ $^{\circ}C^{-1}$ (Harmon, Schwarcz & Ford, 1978). This value does not always apply to biochemically deposited calcium carbonate (Shackleton, Wiseman & Buckley, 1973).

PALAEOTEMPERATURE SOURCES

So far three sources of palaeotemperature information using oxygen isotopes have been utilized.

1. Continental ice sheets. Profiles have been sampled from cores drilled through the Greenland ice sheet at Camp Century and the Antarctic ice sheet at Byrd Station. Variations in the isotopic ratio appear to be controlled primarily by temperature change, low values coinciding with glacial periods and high values with interglacial periods (Langway, Dansgaard, Johnson & Clausen, 1973).

2. Calcareous deep sea sediments. (Mainly in tropical oceans.) Deep sea cores are sampled at regular intervals for shells of particular species of foraminifera and samples analysed for $\delta^{18}O$. Isotopic variations appear to be controlled mainly by the ice volume effect with the crystallisation effect playing only a minor role. Variations are much smaller than in ice cores. Low values coincide with interglacial periods and high values with glacial periods (Shackleton & Opdyke, 1973).

3. Stalagmites. They can be used to provide palaeoclimatic information provided they have formed under conditions of isotopic equilibrium with the

cave seepage waters from which they have been deposited. Isotopic equilibrium means that evaporation of water should play no part in carbonate deposition – deposition must occur in an atmosphere saturated with water vapour. This excludes the use of stalagmites close to cave entrances and probably also from caves in more arid regions.

It is possible to test for equilibrium conditions by carrying out a number of oxygen isotope analyses on a single growth layer which should all yield similar values under equilibrium conditions. It can also be done by carrying out both oxygen and carbon isotope analyses for a number of samples on a single growth layer. In the latter case, if there is a correlation between the $^{18}O/^{16}O$ ratio and the $^{13}C/^{12}C$ ratio the stalagmite was not formed under equilibrium conditions (Thompson, Schwarcz & Ford, 1974).

Caves have the advantage that with rare exceptions they have an almost constant temperature environment (annual temperature variation < 1°C) and the temperature is approximately equal to the mean annual surface temperature above the cave.

If stalagmites formed from seepage water with a constant isotopic composition, then determination of palaeotemperature values would be simple because we would be dealing only with the crystallisation effect, where

$$T = \sqrt{\frac{2780}{\ln K_{c-w} + .00289}}$$

where T is absolute temperature (K)
and K_{c-w} equals $(^{18}O/^{16}O)_c \ / \ (^{18}O/^{16}O)_w$
(from Harmon, Schwarcz & Ford, 1978).

Unfortunately the isotopic composition of seepage water varies. Variation is caused by temperature effects - both short term due to seasonal change and long term due to climatic change.

Fortunately, when calcium carbonate is deposited small amounts of seepage water are trapped in cavities and this water is then sealed in by further deposition to form inclusions. When sealed in, the oxygen isotope composition of the water is representative of the water from which the particular layer crystallised.

If the oxygen isotope composition of the water remained unchanged after sealing, we could determine the isotopic composition and hence the temperature at which the particular layer of calcite formed. However, this is not the case - the oxygen isotope composition may change after inclusion because of exchange with the surrounding calcite (Schwarcz & Harmon, 1970).

By a fortunate circumstance we can reconstruct original oxygen isotope composition of the fluid by measuring its D/H ratio - the ratio of deuterium to hydrogen. Since the surrounding calcite does not contain hydrogen this can be expected to have retained its original value. In all meteoric waters (and seepage waters derived from them) there is a close statistical relationship between the D/H ratio and the $^{18}O/^{16}O$ ratio. The line of best fit is known as the meteoric water line and is represented by the regression equation $\delta D = 8\,\delta^{18}O + 10$.

Hence it is possible to calculate the temperature of formation for those layers for which inclusion waters have been analysed. These values can then be used to calibrate the curve $\delta^{18}O$ against time in terms of temperature change. This must be done for every locality if an estimate of palaeotemperature change is to be obtained.

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CONCLUSION

The techniques outlined in this paper enable the reconstruction of a dated temperature record from stalagmites for the last 300 000 years of the earth's history. Past mean annual temperatures of karst areas, where suitable speleothems are available, can be estimated with a total error of ± 2°C (Harmon, Schwarcz & Ford, 1978). However, relative temperature changes of as little as 0.1°C may be detected.

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SEA CAVES OF KING ISLAND

7

Albert Goede, Russell Harmon and Kevin Kiernan

Abstract

Investigation of two King Island sea caves developed in quartzitic rocks shows them to contain a wealth of clastic and chemical sediments.

Clastic sediments consist of wave-rounded cobbles, debris cones, and angular rock fragments produced by frost weathering and crystal wedging. Chemical deposits include a variety of calcium carbonate speleothems and also gypsum occurring as wall crusts and blisters. The latter appear to be a speleothem type of rare occurrence. Growth of gypsum is responsible for some crystal wedging of the bedrock. Three basal stalagmite samples have been dated by the Th/U method indicating Late Pleistocene as well as Holocene speleothem growth.

The caves are believed to have formed by preferential wave erosion during the Last Interglacial in altered and fractured quartzites. The evidence for pre-Holocene evolution of sea caves and geos in the Tasmanian region is summarized. Tasmania and the Bass Strait Islands provide a particularly favourable environment for the preservation of relict landforms on rocky coasts because of Late Quaternary uplift.

The potential of further studies of sea caves to test two recently advanced archaeological hypotheses is discussed.

INTRODUCTION

Geomorphological investigation, mapping and radiometric dating have been carried out in two sea caves on the SW coast of King Island between Surprise and Fitzmaurice Bays (Figure 1). The northernmost cave, Iron Monarch, is located at 143°52'0"E and 40°4'35"S and the southernmost, Blister Cave, at 143°52'5"E and 40°5'42"S. Iron Monarch was discovered about 1960. It is the more extensive of the two and has not been previously recorded in the literature. Blister Cave was evidently known prior to 1954 as it is reported by Jennings (1956) who gave a description of both it and a small cave nearby.

The field work was done by the senior author who is responsible for the contents of the paper and for any expressed opinions. The Thu/U age determinations were carried out by Russell Harmon while Kevin Kiernan assisted with the field work and the surveys. He also compiled the cave maps.

The caves were selected for detailed study for a number of reasons:

(1) Their morphological characteristics indicate they are of considerable age and predate the Holocene (as suggested earlier by Jennings) despite their occurrence on a cliffed coast subject to strong wave attack.

(2) They contain significant deposits of both clastic and chemical sediments with the possibility of finding material suitable for dating.

(3) They contain well-developed spelothems - an unusual feature of sea caves developed in non-carbonate rocks. The presence of speleothems was explained by Jennings (1956) as being due to a source of calcium carbonate from overlying cliff-top dunes.

PHYSICAL ENVIRONMENT

The geormorphology of King Island has been examined in detail by Jennings (1959) who includes a description of the high coast from Surprise Bay to Fitzmaurice Bay. This part of King Island consists of a plateau surface which reaches its highest elevation of just over 100 metres about 2.5 km east of Blister Cave. From here it slopes down gently in all directions. To the west between Cataraqui Point and Surprise Point this surface is abruptly truncated at an elevation of approximately 40 metres by a cliffed coast subject to strong present day wave attack. In detail the coastal outline is irregular with numerous geos, inlets, natural arches and offshore rocks. The plunging nature of the cliffline was recognized by Jennings (1959) who pointed out that the real break of slope occurred at a depth of approximately 35 to 65 metres and that wave attack might be weakened because of wave

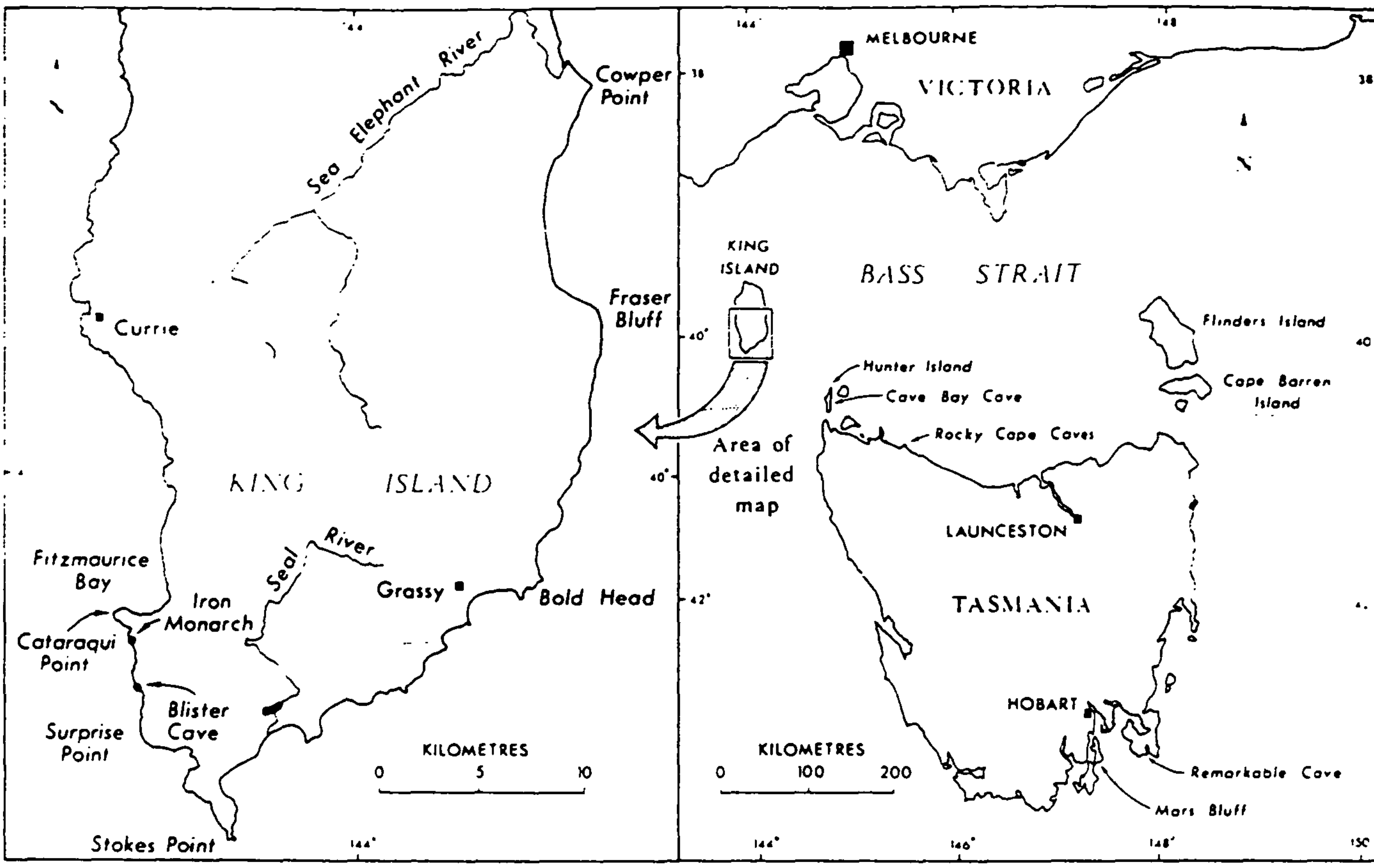

Figure 1. Locality map

reflection. This may help to account for the relict features described by him such as raised marine platforms, hanging coves, raised sea caves and slope breccias - deposits of angular rock fragments set in a sandy matrix and cemented either by sesquioxides or calcium carbonate. These deposits were locally observed to have accumulated on platform remnants. The breccias were regarded by Jennings as the product of subaerial weathering under cold climate conditions. Dated evidence of accelerated physical weathering at sea level during the last glacial period in nearby areas had recently been found by Bowdler (Hope, 1978) in a raised sea cave in Hunter Island while one of the present authors (Murray and Goede, 1977; Goede, Murray and Harmon, 1978) has found evidence of the same phenomenon in a limestone cave less than 40 metres above sealevel SSW of Montagu in NW Tasmania.

In places the plateau margin adjacent to the coastal cliffs is overlain by accumulations of calcareous dune sand. The problems posed by such accumulations in a cliff-top position have been examined by Jennings (1967) in relation to this and other areas. The relevance of these sands in the context of the present paper is as a probable source of calcium carbonate for the considerable development of speleothems that has taken place in the two sea caves described.

The rocks making up the coast in which the sea caves have developed are strongly folded metamorphic rocks such as phyllites, schists and quartzites of presumed (?) Precambrian age. They are intruded by granitic rocks at Cataraqui Point a short distance north of Iron Monarch. In the area of the caves the metamorphic rocks dip steeply in an ESE to SSE direction.

IRON MONARCH

The Iron Monarch is an impressive sea cave located nearly two kilometres SSE of Cataraqui Point. At the seaward end is a prominent geo which for the first 45 metres from the open sea is permanently water-filled and has an estimated width of up to ten metres (Plate 1). From here a steep-sided fissure extends inland for another 130 metres of which the first 52 metres is open to the sky leaving a final 80 metres of sea cave (Figure 2). The whole feature has developed by preferential erosion of a narrow sequence of beds dipping to the ESE at an angle of 80°. These beds appear to be more massive and less contorted than the surrounding beds. The trend of the fissure is closely controlled by the strike of the beds. The datum level for the cave surveys was taken to be the upper level of calcareous marine tube worms (*Serpula* sp.) and all survey heights are related to this datum. From the sea's edge the lowest part of the fissure is some eight metres wide and filled with large wave-rounded boulders. The fissure then narrows to between 3 and

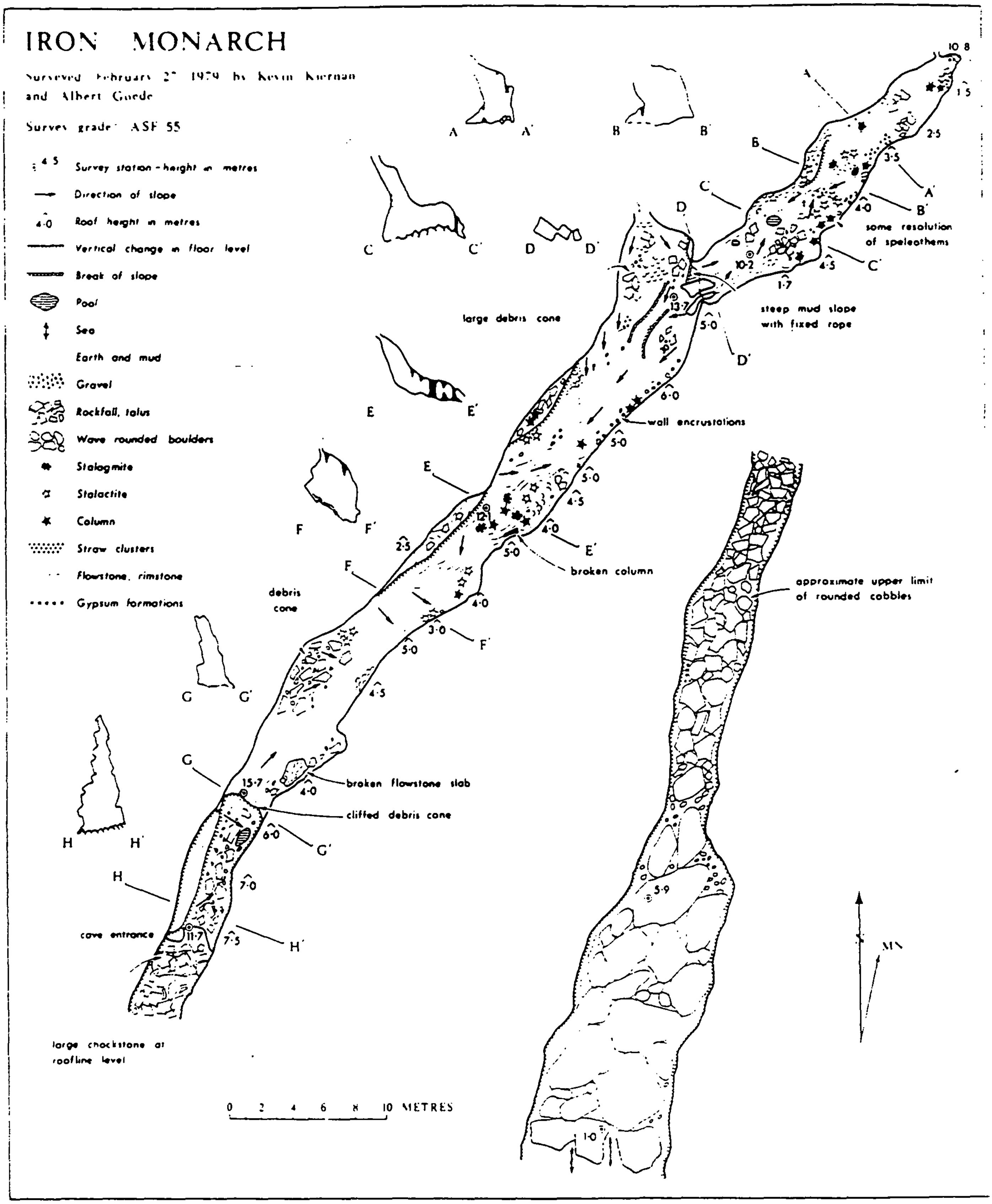

Figure 2. Survey of Iron Monarch

4 metres and angular breakdown of various sizes becomes the dominant floor material. At the roof line there is a low rampart of debris which in recent times has accumulated from the cliff above. Elevation of the crest is 11.7 metres. Ponding of water behind the rampart has formed a shallow muddy pool.

Immediately behind rises a wave eroded cliff of well compacted breccia containing blocks up to 50 cm in diameter in a fine-grained matrix (Plate 2). The cliff rises almost vertically but can be climbed on the western side. At the top of the cliff (15.8 metres elevation) the cave floor slopes downwards into the first chamber until it reaches an elevation of approximately 12 metres with a maximum passage width of five metres and a maximum roof height of six metres. In detail the floor is rather irregular as some angular breakdown of the walls has occurred. At one place on the western side a considerable amount of debris has been fed in from a roof shaft which presumably once had a connection with the surface.

At this point the roof drops sharply and a steep muddy slope leads into the second and final chamber which is some 20 metres long and an average 3 to 4 metres wide and has a floor level between 10 and 11 metres above datum. This is the most abundantly decorated part of the cave (Plate 3).

The largest and best exposed clastic deposit occurs just inside the entrance (Plate 2). It represents the remains of a debris cone which at one time appears to have almost blocked the cave entrance and must have been built up by large amounts of material coming from the slopes above down over the roofline (at this point only 50 cm wide as the cave narrows upwards). Subsequent to its deposition the fan was cliffed back by wave action exposing an almost vertical section up to 4.5 metres high. The breccia consists of a wide size range of angular rock fragments up to 50 cm in diameter set in a matrix of sandy and clay rich sediments. In the lower part of the section the sediments are cemented by and encrusted with calcium carbonate. Stone content varies significantly with rock fragments largest and most abundant in the middle layers of the section. In the basal beds the matrix is a greyish olive (5Y/5/2) clayey sand. In the middle layers the matrix is a greyish brown clay (5YR/5/2) with bright reddish brown mottles (5YR/5/6). The middle layers are overlain by a band of laminated dark olive grey 2.5GY/3/1) clay from 4 to 10 cm in thickness. The upper layers have a dull yellowish brown matrix (10YR/4/3 to 5/4) of silty sand containing small rock fragments and are interbedded with at least one thin layer of clay. The clay layers were probably deposited when water was ponded back behind the growing debris cone. Insufficient charcoal was present for ^{14}C dating. No bone material was found in the deposits.

The debris cone associated with the roof shaft further inside the cave remains largely undissected and consists of angular blocks of bedrock in a muddy matrix. Some of the rock fragments are covered with muddy flowstone indicating that the fan has not been active for a considerable time.

Other parts of the cave floor are covered with angular breakdown from the walls. Most of this may be due to frost weathering under cold climate conditions but the south-east wall in the first chamber shows encrustations of a white crystalline mineral with evidence that crystal wedging by this material has produced angular breakdown. Flakes of rock can be seen in various stages of being wedged away from the wall by the growth of a crystalline substance. However, lack of recent accumulation of angular material on the floor at this site indicates that the process is not currently active. X-ray diffraction analysis by R. Ford (pers. comm.) has shown this mineral to be gypsum. The ability of gypsum to produce angular breakdown by crystal wedging is well known.

The original floor of the cave is nowhere exposed and no wave-rounded material was found. The survey indicates that this floor could not have been higher than 10 metres above datum at the inland extremity of the cave.

The cave is particularly well decorated and has suffered little vandalism. The first chamber contains the most massive speleothems. The largest columns in the cave are found here with the tallest being over two metres in height (Plate 4). They appear to be composed of very impure calcium carbonate with iron oxides as an important impurity. Some of the columns show definite signs of being corroded at present. Impure flowstone also occurs and near the entrance is covered with a green algal mat.

The second chamber is virtually in the dark zone because of the small steeply sloping opening which connects it to the first. The formations appear to be much purer with a dense crystalline structure. Stalactites (including straws), stalagmites , flowstone and small rimstone pools are present and active deposition is taking place (Plate 3). Colours vary from white to orange brown and dark brown. Some re-solution of speleothems was observed at the far end of the chamber. A small stalagmite which had been broken from the floor was collected for possible Th/U radiometric analysis to determine its age and a sample of the wall bedrock was removed for petrological analysis.

BLISTER CAVE

This cave is briefly described by Jennings (1956) together with another smaller cave nearby with two entrances and at a lower elevation. The smaller cave was visited and roughly sketched.

The entrance to Blister Cave is located in the SE corner of a natural amphitheatre surrounded by vertical cliffs. The floor of the amphitheatre consists of an accumulation of angular rock debris of various sizes sloping down towards the sea at an average angle of 20°. Below the cave entrance, which is quite low, is a wave cliffed debris cone with an exposed face 3 metres high and rather similar in appearance to the one found inside the entrance to Iron Monarch (Plate 5). The base of the cliff is at an elevation of approximately 18.5 metres with the entrance floor at 21.5 metres. The debris cone does not appear to be subject to wave attack at the present time. Angular fragments of bedrock up to 60 cm long are imbedded in a matrix of yellow brown to reddish brown earth. No charcoal or bone was found in the sediments. The inner side of the cone slopes down into the cave at approximately 35°. The cave has developed parallel to the strike of the steeply dipping beds and is aligned on a bearing of 61° true north (Figure 3). Beyond the foot of the slope the floor is covered with angular rock fragments and again there is evidence that some of it is due to crystal wedging by gypsum - a process inactive at present. The length of the cave is only 40 metres with a bifurcation of the passage at the landward end. Wave rounded boulders, the largest 50 cm in diameter, are found on the floor of the cave near the far end where the altitude is approximately 14.4 metres. Some are capped with flowstone, one with a 20 cm high stalagmite.

Jennings (1956) described the cave as well decorated but most of the speleothems have since been removed. One column approximately 20 cm in diameter and 50 cm high remains. Two small stalagmites, already broken or disturbed, were removed for Th/U dating and a bedrock sample was collected for petrological analysis.

The most outstanding remaining decoration consists of blisters of white crystalline material on part of the ceiling and upper walls (Plate 6). The largest of these are approximately 10 cm in diameter and where broken can be seen to consist of a thin crust (2 to 4 mm) surrounding a hollow centre (Plate 7). They were also observed by Jennings (1956) who believed them to be calcite but X-ray diffraction analysis of a sample shows them to be gypsum (Ford, pers. comm.). This mineral is also responsible for crystal wedging of bedrock in both Blister Cave and Iron Monarch.

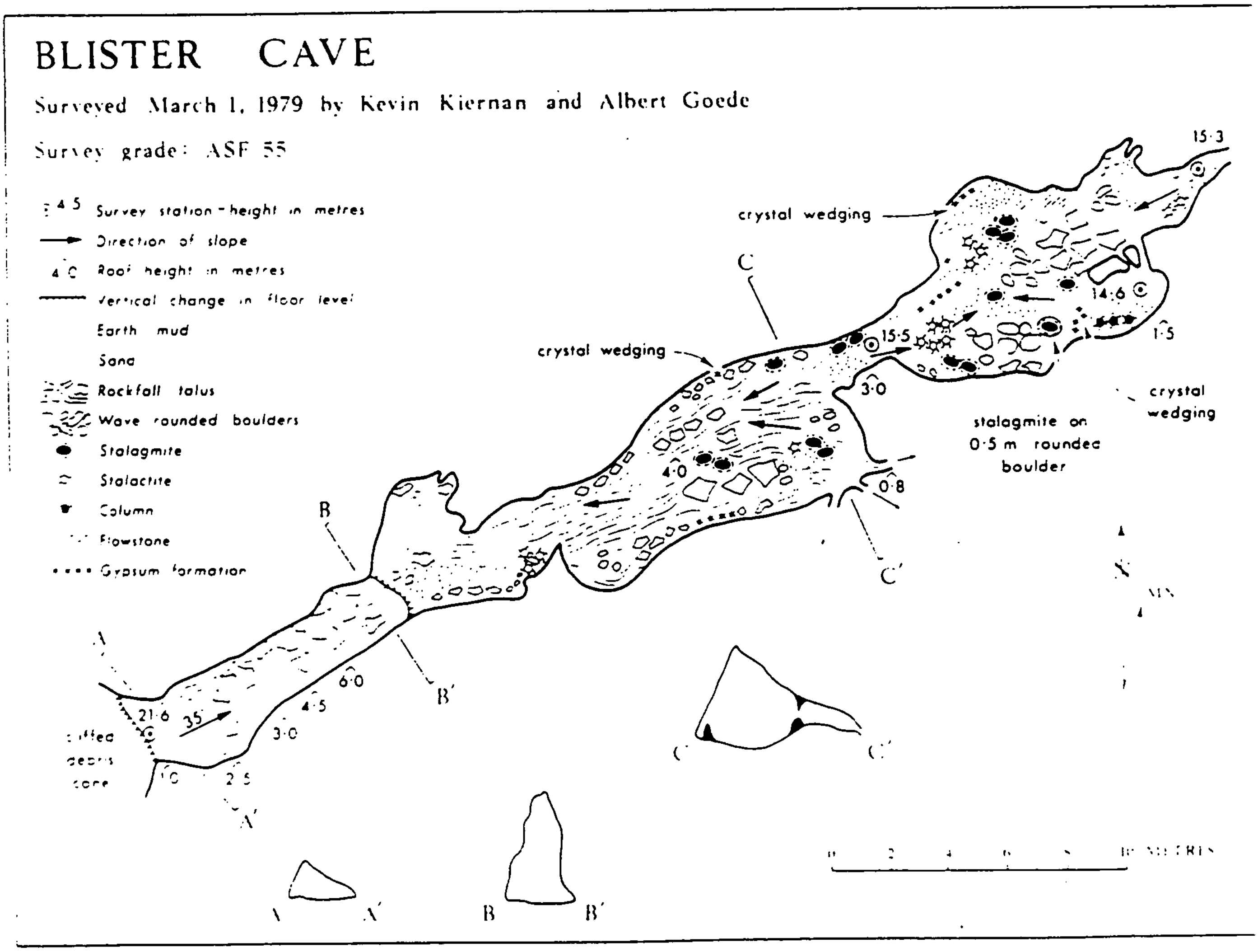

Figure 3. Survey of Blister Cave

LITHOLOGY

Iron Monarch has developed as a result of preferential wave erosion of a narrow sequence of steeply dipping massive beds of quartzite interbedded with much more highly contorted schistose beds.

A sample of wall rock collected from the cave was examined by I. Naqui (pers. comm.) who described the hand specimen as a greenish grey (5GY6/1) coloured, hard, finely crystalline rock with fractures. In thin section it is found to be a fine-grained, holocrystalline, brecciated rock composed of quartz (70%), altered plagioclase feldspar (10%), chlorite and haematite (20%). It contains numerous cavities parallel to the fracture planes and secondary silicification is common. It is quartzitic rock strongly affected by the intrusion of the Cataraqui Point granite. The granite contact occurs a short distance to the north.

The preferential erosion of quartzite is unusual and appears to be due to strong fracturing and development of cavities parallel to the fracture planes facilitating both physical and chemical weathering. The fractures also provide ready made routes for meteoric water percolating from the surface and probably account for the relative abundance of speleothems.

Blister Cave is located in a sequence of steeply dipping quartzite beds. A hand specimen from inside the cave was described by Naqui (pers. comm.) as a medium light grey (N6) coloured, hard, foliated, quartzitic rock with small cavities aligned parallel to the foliation.

In thin section it consists of interlocking quartz (70%) and some plagioclase feldspar (10%) crystals parallel to the foliation. Fractures are common both parallel to the foliation plane and at 80° to it (Plate 8). They are partly filled with chlorite, sericite (20%) and silica. The rock is a quartzite. Preferential erosion would have been encouraged by the strong fracturing of the rock and the high mica content.

DATING

Radiometric age determinations ($^{230}Th/^{234}U$) were carried out on one basal stalagmite sample (UT75) from Iron Monarch and two (UT77 and UT78) from Blister Cave. Uranium analysis (delayed neutron technique) by the Australian Atomic Energy Commission had previously indicated the presence of high concentrations of uranium. Results are shown in Table I.

The sample from Iron Monarch is late Holocene while the two from Blister Cave are late Pleistocene in age. The last two dates clearly indicate that Blister Cave could not possibly have formed during Holocene high sealevels even allowing for the remote possibility of significant uplift of the coast during post-glacial times.

Since Iron Monarch has experienced a very similar depositional history to Blister Cave we can assume that the origin of both caves dates at least as far back in time as the Last Interglacial. The dates confirm the view of Jennings (1959) who suggested that the abandoned sea caves along this part of the coast were part of the "Old Shoreline System" which he provisionally attributed to the Last Interglacial.

TABLE I - URANIUM CONCENTRATIONS, ISOTOPE ACTIVITY RATIOS AND AGES OF SPELOTHEMS

Sample Number	U conc. (p.p.m)	$\frac{^{230}Th}{^{234}U}$	$\frac{^{234}U}{^{238}U}$	$\frac{^{230}Th}{^{232}Th}$	Age (10^3 years BP)
UT-75	10.4	.01 ± .003	1.68 ± .005	56	2
UT-77	37.8	.15 ± .03	1.64 ± .01	782	17 ± 3
UT-78	8.0	.17 ± .04	1.46 ± .01	399	19 ± 4

Plate 1. (above)
Geo leading to entrance of Iron Monarch viewed from cliff edge. Note figure on right.

Plate 2. (left)
Entrance to Iron Monarch with cliffed debris cone.

Plate 3. Decoration in second chamber of Iron Monarch.

Plate 4. Large column in first chamber of Iron Monarch. Note figure for scale.

Plate 5. Cliffed debris cone below entrance to Blister Cave

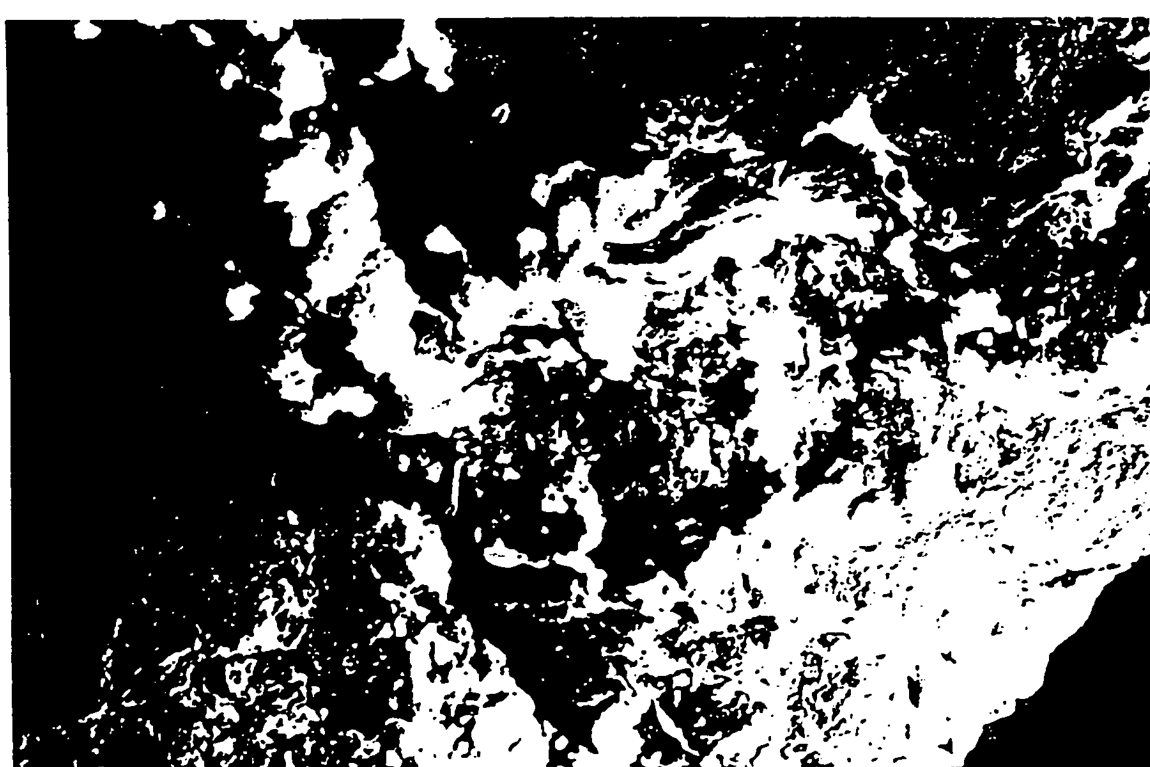

Plate 6. Gypsum blisters in Blister Cave

Plate 7. Large broken gypsum blister showing hollow interior

Plate 8. Quartzite bedrock in Blister Cave. Thin section under ordinary light, 30X. Note fractures. (Photo by Ikram Haqu.)

EVOLUTION OF THE CAVES

The caves were formed by wave erosion, most probably during the high sealevel stands of the Last Interglacial. Their formation requires a sealevel higher than the present. Jennings (1959) concluded that the "Old Shoreline System" showed evident of a falling sequence of sealevels from 28 metres down to the present level with marked stillstands at 12 to 15 metres and 6 to 9 metres. The floor of the second chamber in Iron Monarch varies between 10 and 11 metres above sealevel, while the innermost part of Blister Cave, where wave-rounded boulders are still exposed, has an elevation of 14 to 15 metres. The inferred evolutionary history of Iron Monarch is shown in Figure 4.

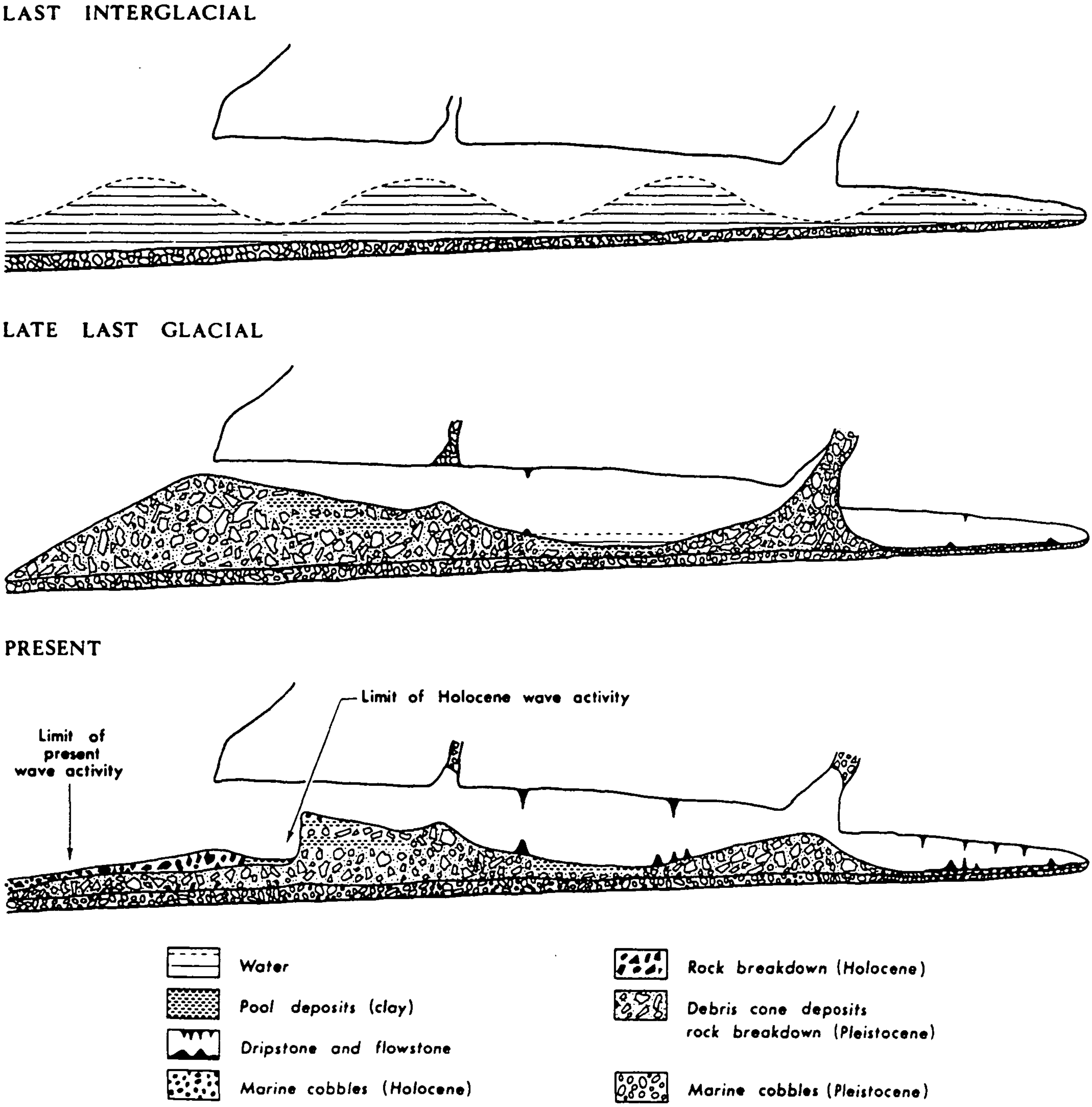

Figure 4. Evolutionary sequence of cave development for Iron Monarch

During the Last Glacial when the sea had retreated westwards to a lower level, instability of the slopes above the cliffs caused accumulation of debris cones in front of the entrances. In the case of Blister Cave it appears likely that the entrance was completely sealed. In Iron Monarch significant ponding of water occurred inside the cave as indicated by the clay layers in the sedimentary sequence. Examination of these clays for the presence of pollen and ostracods may prove rewarding.

Some physical weathering of the cave walls also appears to have taken place about this time as there are accumulations of angular breakdown which are clearly fossil in both caves. Both they and the debris cones can be expected to be contemporaneous with the slope breccias described by Jennings (1959) along that part of the coast.

In the Holocene the sealevel rose and wave erosion removed a large part of the debris cones leaving a near vertical wave eroded cliff in each case (Plates 2 and 5). At the entrance to Iron Monarch a low rampart of debris derived from the cliff above has since developed in front of the cliffed cone creating a shallow mud-floored depression in between. This indicates that the cone has not been subject to wave attack for some considerable time. Either a marginally higher sealevel has been responsible or slight uplift of the coast has occurred during the late Holocene.

The Th/U dates and the large size of some speleothems support a long evolutionary history for the caves. While some stalagmites are being corroded, possibly indicating environmental changes, others appear to be actively growing.

Crystal wedging of bedrock walls by gypsum associated with wallcrust has occurred on a minor scale in both caves. In Blister Cave areas of crystal wedging are closely associated with the occurrence of gypsum blisters. Since the latter are absent in Iron Monarch it could indicate that they developed when Blister Cave was completely sealed.

Gypsum blisters appear to be an unusual form of speleothem rarely mentioned in the literature. White (1976) claims that blisters are an intermediate stage in the development of gypsum flowers (oulopholites) from wall crust. If the Blister Cave specimens represent such a stage it is surprising that no gypsum flowers are present.

Since the country rock is know to be mineralized sulphide minerals are the most likely source of gypsum. When they are oxidized the resulting sulphuric acid would react with carbonate rich seepage waters to form gypsum (White, 1976).

DISCUSSION

Despite the rapid growth of geomorphological research in Australia during the last twenty years, sea caves and associated features of rocky coasts appear to be a neglected field. This is probably due to their being regarded as erosional landforms which by their very nature can tell us little about their evolutionary history.

Our study of two King Island sea caves has shown that such landforms can be of considerable age and may contain a variety of clastic and chemical deposits. The presence of speleothems in caves developed in non-carbonate rocks may seem surprising but could be relatively common (Baker and Frostick, 1947). Speleothems can be dated by the $^{230}Th/^{234}U$ method. In this case U concentrations are unusually high due to the presence of mineralization in the host rock. However, samples containing as little as 0.1 p.p.m uranium can be successfully dated by this method as long as there is no detrital contamination.

Holocene wave erosion of rocky coasts can only have taken place during the last 6000 years, the length of time sealevel has been near or at its present level (Thom and Chappell, 1975). Our research adds to evidence indicating considerable age for a number of erosional landforms associated with the rocky coasts of Tasmania and the Bass Strait Islands. Many landforms appear to relate to the high sealevels of the Last Interglacial (approx. 130,000-75,000 years BP), the last pre-Holocene period when world-wide sealevels stood close to or above those of the present (Thom, 1973).

In the last few years considerable evidence of pre-Holocene evolution of sea caves and geos has emerged. Bowdler (1974, 1975) investigated an archaeological sequence in Cave Bay Cave, a raised sea cave on the east coast of Hunter Island, and demonstrated aboriginal occupation dating back to 23,000 years BP. Jones (1971) has shown that sea caves at Rocky Cape contain an archaeological record dating back some 8,000 years.

Colhoun (1977) described a sediment-filled geo associated with Remarkable Cave in southeastern Tasmania. Seventeen metres of unconsolidated sediments were present with basal beach sediments overlain by slope and valley fill deposits. The latter contained plant remains, pollen, charcoal and fossil wood. Five ^{14}C dates obtained from different stratigraphic horizons all yielded ages in excess of 37,000 years BP. Formation of the geo probably occurred during the Last Interglacial.

Burns (1977) reported the occurrence of remnants of indurated slope deposits located in geos at Mars Bluff on Bruny Island off the southeast Tasmanian coast. He interprets them as having accumulated as a result of slope instability under cold climate conditions. He concludes that "the present cliffline is, at least in part, relic from the Last Interglacial, and possibly earlier higher sea levels."

The Tasmanian region may provide a particularly favourable environment for the preservation of Pleistocene landforms on rocky coasts as there is evidence of late Quaternary uplift. Marine deposits believed to be of Last Interglacial age occur at elevations of up to +20 metres along the northwest coast, +22 metres at Strahan on the west coast and also at Swansea and Mary Ann Bay in the southeast (Van de Geer, Colhoun and Bowden, 1979). In northeastern Tasmania similar deposits can be identified up to +32 metres (Bowden, 1978).

This should be compared with evidence that on stable coasts maximum heights of Last Interglacial sea levels reached only +2 to +8 metres, both within Australia (coast of N.S.W.) and on other continents (Marshall and Thom, 1976).

Sea caves should recive much closer attention as highly favourable potential locations for Pleistocene aboriginal sites. Singh, Kershaw and Clark (1979) have presented tantalizing evidence from pollen analysis of greatly increased burning around Lake George, N.S.W. during the Last Interglacial compared with earlier Interglacials, as indicated by the dominance of fire adapted taxa and the greatly increased content of charcoal particles in the lake sediments. They have speculated that this may be associated with the first arrival of man in Australia. If so, man can be expected to have arrived during the Penultimate Glacial (195,000-130,000 years BP) when sealevels were low. Another question is whether he would also have reached Tasmania during the same period.

Since many sea caves appear to have formed during the high sealevels of the Last Interglacial (125,000-100,000 years BP) they could have provided shelter at any time during the last 100,000 years of Australian prehistory.

Sea caves also warrant close examination to test the archaeological hypothesis put forward by Bowdler (1977) that Australia was colonized by people adapted to a coastal way of life. Whenever sealevels were relatively high as for example 80,000 years ago, sea caves would have provided suitable shelter within easy reach of coastal and marine food resources. They may have done so even when sealevels were low, along coasts where the continental shelf is narrow as is the case off the west coast of King Island.

If the hypotheses of Singh et al. (1979) and Bowdler (1977) are both correct we can expect to discover archaeological sites very similar to those found in raised sea caves along the coast of Southern Africa (Nelson Bay Cave and Klasies River Mouth Caves) where Middle Stone Age occupation has been found dating back to the Last Interglacial (Klein, 1975, 1979). At present the South African sites provide the oldest evidence for regular exploitation of marine resources anywhere in the world (Klein, 1975).

Sea caves, even where developed in non-carbonate rocks, frequently provide suitable preservational environments for shell and bone because of the absence of leaching by percolating water which rapidly destroys such archaeological materials at surface sites. As such they have the potential to provide most favourable sites to test one or both of the above archaeological hypotheses. Where deposition of carbonate minerals has occurred they also offer the opportunity of dating very early human occupation sites by means of Th/U analysis.

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PLEISTOCENE HUMAN OCCUPATION AT BEGINNERS LUCK CAVE, FLORENTINE VALLEY, TASMANIA

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Abstract

EVIDENCE of human occupation dated at approximately 20,000 years BP is recorded from a cave site in the Florentine Valley in south central Tasmania. The artifact assemblage and faunal content are described and the factors giving rise to bone accumulation are examined.

Occupation has been dated by ^{14}C analysis of associated charcoal and aspartic acid racemization dating of bone with close agreement between the two methods.

The interior river valleys of southern Tasmania were being utilized by hunter-gatherers when the Last Glacial was reaching its climax and Tasmania was a peninsula of the Australian mainland. Suggestions by recent authors that late Pleistocene occupation was tightly coastal and that the interior was uninhabited are refuted.

Under the open vegetation conditions prevailing during the late Pleistocene the broad river valleys of southern Tasmania provided easy routes for population movement and a suitable environment for game. In contrast dense wet forest was the dominant vegetation throughout the Holocene making these areas less attractive for both human occupation and the larger elements of the fauna.

Introduction

The archaeological significance of site P in Beginners Luck Cave (Fig. 1) was first recognized in 1975 during the investigation of several late Pleistocene fossil bone deposits within the cave. Goede and Murray (1977) published a site description and presented evidence of human association. They also discussed the stratigraphy, palaeontological content and probable age of the deposit. The age estimate was based on a single ^{14}C date and its limitations were discussed.

In late 1977 a systematic excavation was carried out in order to obtain further archaeological and palaeontological material and to collect additional charcoal for ^{14}C dates with finer stratigraphic control. Asparctic acid racemization age determination on bone was also carried out.

Excavation techniques

An exposure of breccia adhering to the

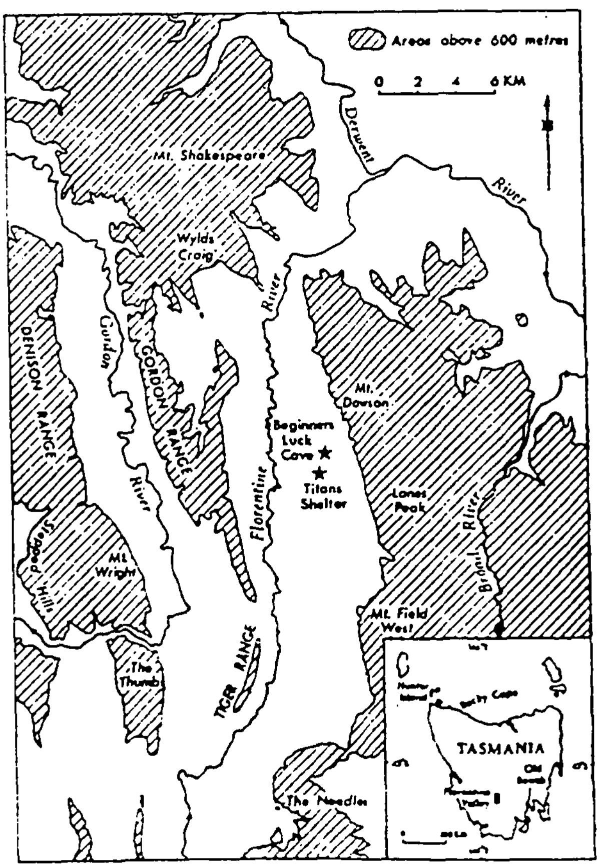

Figure 1. Locality map.

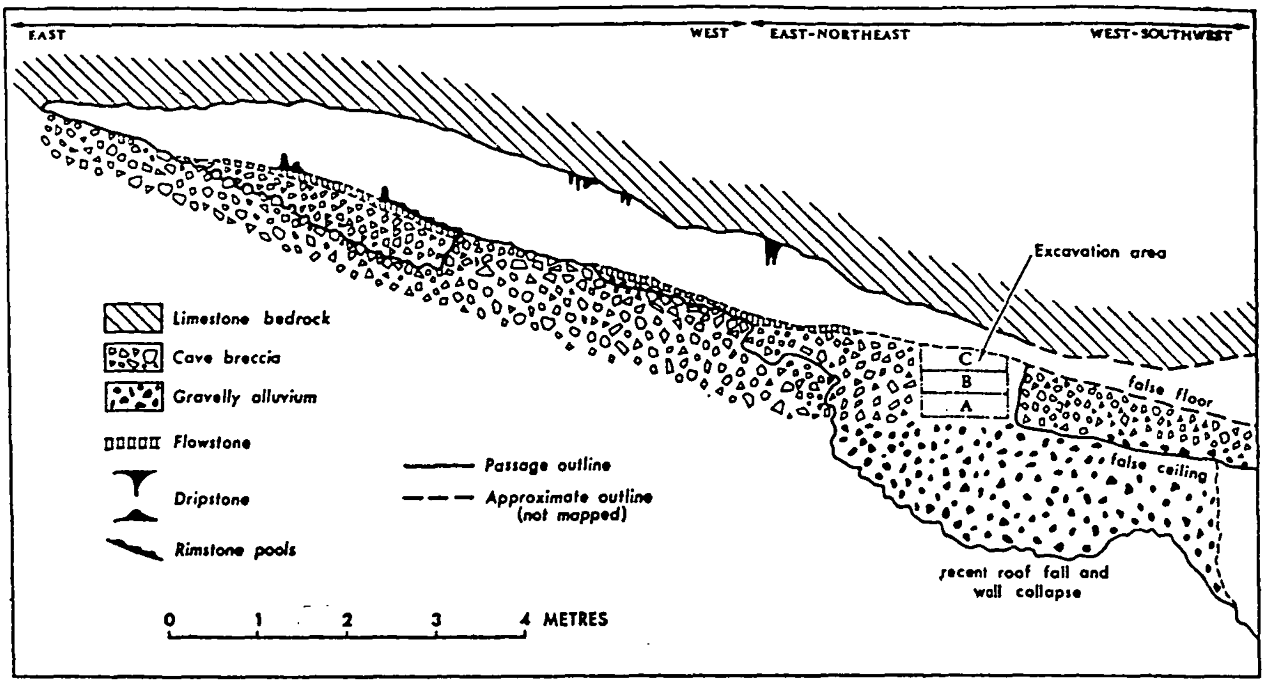

Figure 2. Generalized longitudinal section of passage at site P.

northern wall of the passage (Fig. 2) and approximately 75 cm thick provided a clean profile of undisturbed material for excavation. Two artifacts were already exposed in the face due to preferential erosion of less consolidated material in the centre of the passage. The excavation was made one metre wide and was extended back to the bedrock wall — a distance of approximately 60 cm at the surface of the deposit, but increasing slightly with depth due to the outward curvature of the passage wall. An arbitrary datum was established near the top of the planned excavation.

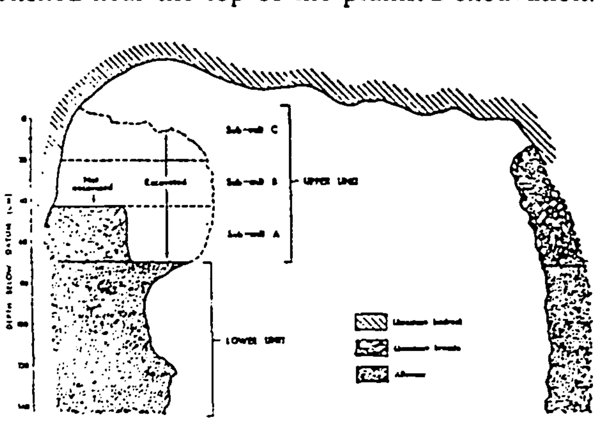

Figure 3. View of excavations in relation to stratigraphy seen in passage cross section, site P.

The site was then drawn and photographed before and during excavation (Figs 3, 4 and 5).

The breccia was excavated with a heavy mallet and an assortment of chisels. Material was removed in layers approximately 5 cm thick, but close stratigraphic control was difficult to maintain due to irregular fracturing of the breccia when broken up. Loose material was trowelled into plastic buckets for detailed examination and screening of the contents on the floor of the passage. The majority of the artifacts and most of the larger bone fragments were recovered *in situ*. The exact position of each of the artifacts was recorded.

Small charcoal fragments were collected separately for each of three sub-units to provide material, it was hoped, for three ^{14}C dates in stratigraphic order.

Stratigraphy

The broad outlines of the stratigraphy have been described in an earlier paper (Goede and Murray 1977). Two lithostratigraphic units are present at the excavation site. The lower unit consists of alluvial sediments with gravels of varied lithology set in a matrix

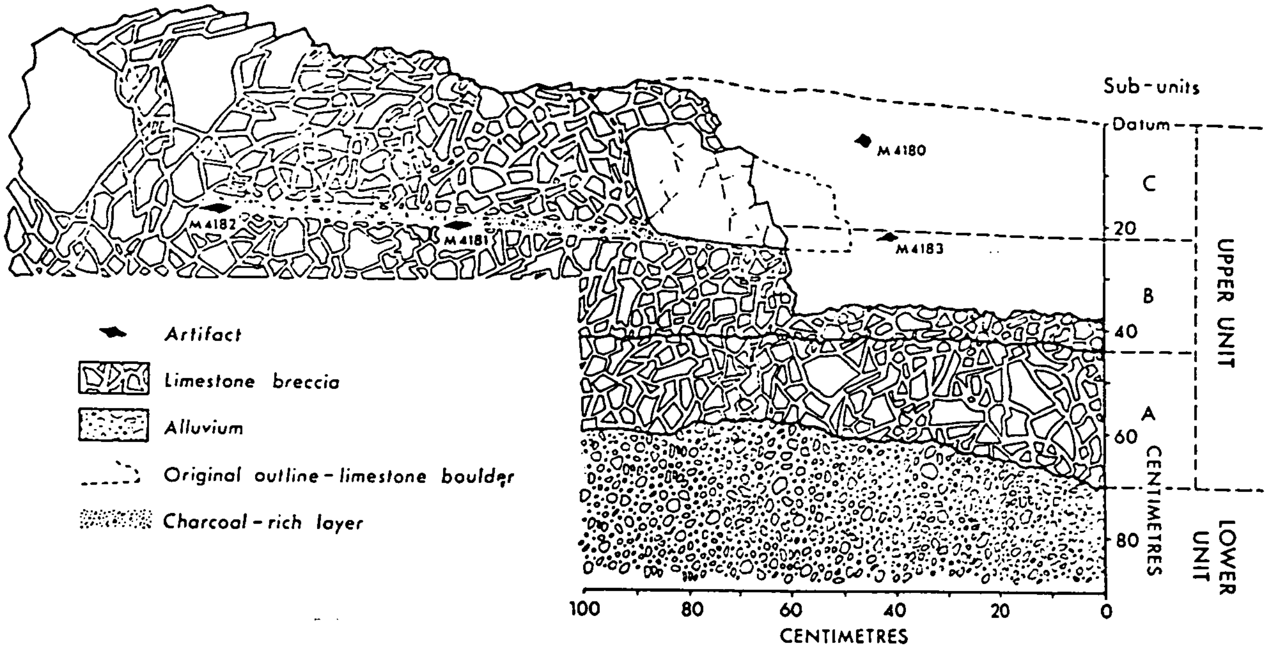

Figure 4. Lateral view of site P during excavation of sub-unit B.

of poorly sorted clayey and silty sands. Charcoal and artifacts appear to be absent from this unit, but it contains small amounts of fragmented bone in its uppermost horizons. The deposit is of unknown thickness. Two metres are exposed in the northern wall of the passage and immediately below the excavation site.

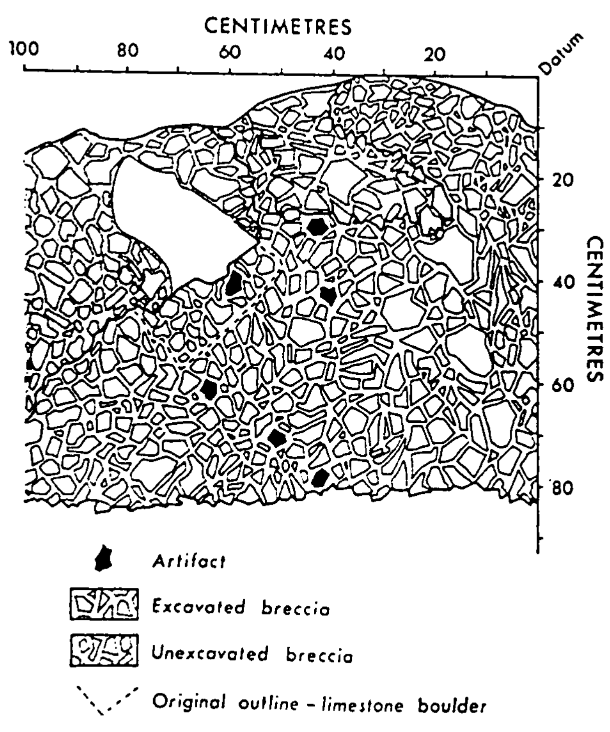

Figure 5. Plan view of site P during excavation of sub-unit B.

The upper unit consists of a limestone breccia of angular fragments in a sparse matrix of sticky brown clay. It is an entrance facies deposit of cryoclastic origin which reached its present position as a debris flow from a former entrance which was completely blocked during the course of its accumulation. It is characterized by the presence of abundant fossil bone in association with stone artifacts and charcoal flecks.

In outcrop, the upper unit appeared to be stratigraphically homogeneous. For analytical purposes it was arbitrarily divided into three sub-units of approximately equal thickness (c. 25 cm) with boundaries parallel to the stratification. The sub-units were labelled A, B and C, A being the lowest. A was only partially excavated (about 40 cm nearest the face) due to its being progressively more cemented towards the cave wall. During excavation, differences in the character of sub-unit C became apparent. In the following descriptions the vertical range of each sub-unit is stated in relation to the datum established for the excavation.

Sub-unit C (+5/-20 cm) contained a single quartzite flake (M4180) which was recovered near the top. Fossil bone and charcoal were scarce. The sub-unit was less cemented and was characterized by a more open framework than the lower sub-units. Unusually heavy cementation was encountered at the base of the sub-unit, apparently as a result of ponding of carbonate rich solutions on the less permeable material below (Fig. 4).

Sub-unit B (-20/-45) contained 13 stone artifacts and was proportionally rich in vertebrate remains. The artifacts were distributed throughout the sub-unit but with a greater concentration in the upper part (-20/-30 cm). A thin band of small charcoal fragments, clearly reworked by water, was visible within this horizon. Three artifacts were recovered in association with this feature. Sub-unit B also yielded several burnt bone fragments. Partially articulated bones of *Thylogale* were found in the strongly cemented material close to the back wall of the excavation.

Sub-unit A (-45/-70 cm) contained few fossil bone fragments, sporadic charcoal particles and a single hornfels flake (M4194). A quartzite pebble (M4193) was also recovered, but this may have been derived from the underlying alluvium as there has been slight mixing of material from the upper and lower units at the contact.

Artifacts

Sixteen stone artifacts were recovered from sub-units A, B and C. They are held in the Tasmanian Museum and Art Gallery, and are referred to by catalogue number. Typologically crude, thick amorphous flakes predominate (Fig. 6). Two small cores were also recovered (e.g. Fig 7A). In general, the flakes display a wide striking platform, low, flat or diffuse bulb of percussion and the tendency to taper sharply distally producing a wedge-shaped profile. Careful retouch is present on two artifacts and some show wear from use. The artifacts range from small to medium sized (20.4 x 16.5 mm-91.5 x 49.0 mm) and were produced from quartzite and cherty hornfels of at least three different lithological types. With one exception (M4196), all hornfels flakes have a light brown weathering rind or patina due to hydration. Outcrops of cherty hornfels have not been identified in the Florentine Valley but could be present. Quartzite occurs locally in alluvium. It has been derived from Permian sediments as glacial erratics in tillite, and glacial dropstones in shallow marine deposits. Quartzite is available at the site from the alluvial deposits but comprises less than one-third of the artifact sample (Table 1).

Debitage is rare in the deposit suggesting that flake production may have taken place elsewhere. Some flakes have low relief bulbs of percussion and are hinge fractured distally (Fig. 6, B, E, H). These flakes also display complex fracture radians indicating that per-

Table 1. *Artifacts by sub-unit from upper unit, Site P, Beginners Luck Cave.*

Sub-unit	Catalogue No.	Description
C	M4180	Quartzite flake (Fig. 6G); 35.4 x 20.7 mm.
	M4181	Thick flake, cherty hornfels (Fig. 6B); 33.0 x 29.0 mm.
	M4182	Retouched flake scraper cherty hornfels (Fig. 6A); 43.0 x 38.0 mm.
	M4183	Flake, grey cherty hornfels; (Fig. 6H); 38.5 x 30.0 mm.
	M4186	Quartzite manuport.
	M4187	Quartzite manuport.
	M4188	Flake, brown cherty hornfels; 46.0 x 43.5 mm.
	M4189	Flake, quartzite (Fig. 7B); 53.0 x 32.5 mm.
B	M4190	Flake, grey cherty hornfels (Fig. 6F); 36.0 x 33.0 mm.
	M4191	Flake, grey cherty hornfels (Fig. 6E); 36.0 x 32.5 mm.
	M4192	Core, grey cherty hornfels (Fig. 7A); 91.5 x 49.0 mm.
	M4195	Core, quartzite; 56.0 x 40.5 mm.
	M4196	Flake, light grey cherty hornfels (Fig. 6D); 48.5 x 34.0 mm.
	M4197	Flake, cherty hornfels (Fig. 6C); 20.4 x 16.5 mm.
A	M4193	Quartzite manuport.
	M4194	Flake, grey cherty hornfels; 32.0 x 17.5 mm.

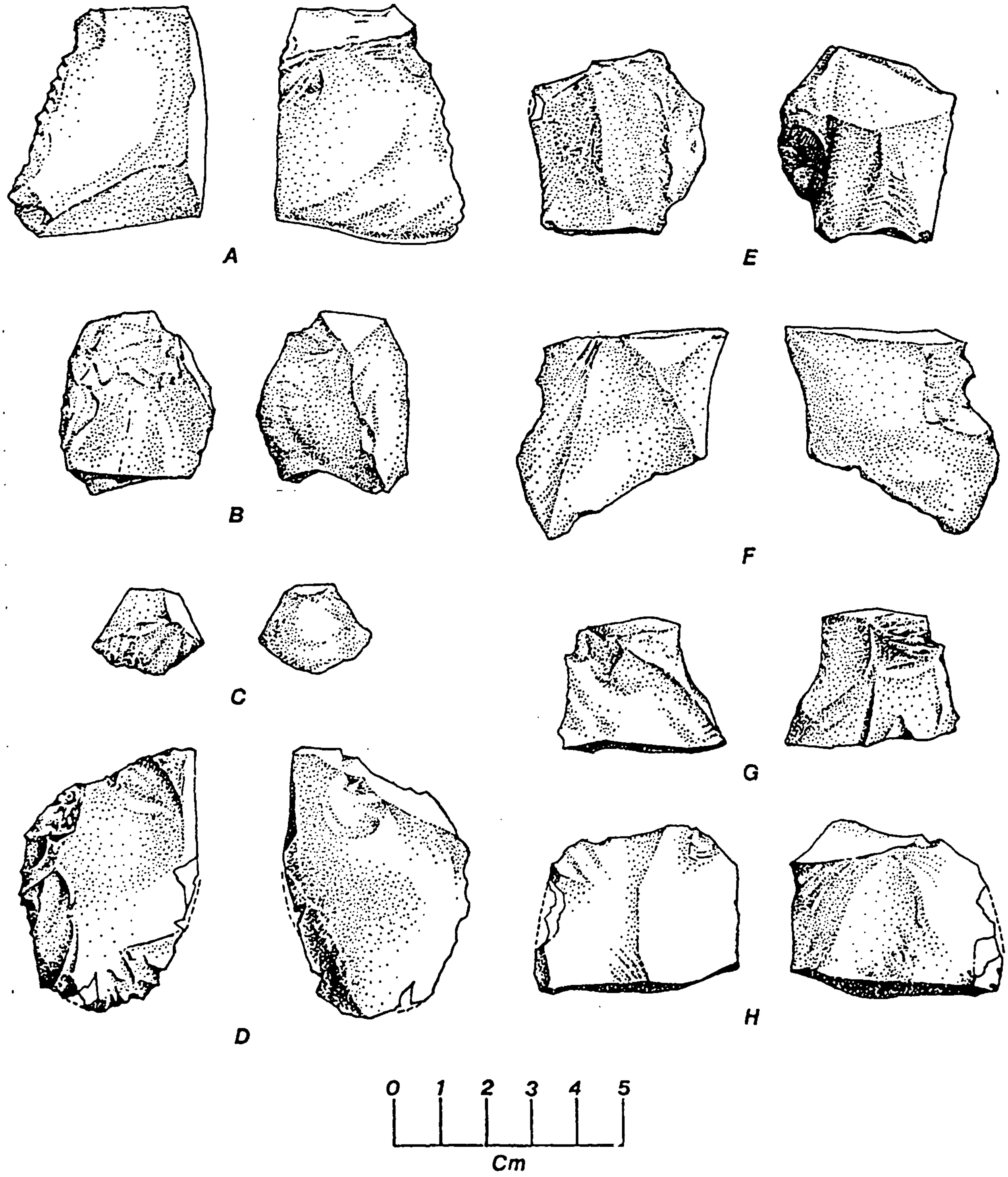

Figure 6. Flakes from site P. Flakes are oriented with the striking platform up.

cussive forces have travelled through the stone unevenly. Two specimens have radiating fracture lines emanating from both the platform and the distal end (Fig. 6 E, H).

Because food was apparently consumed in the cave, it is not unlikely that some of the flakes were employed in skinning and light butchering or dismemberment of joints. The generally light wear on those flakes showing signs of wear would be more comparable with this activity than with working harder substances, such as wood or bone.

Fauna

At least five marsupial and one placental species are represented by the 983 bone fragments recovered. *Macropus rufogriseus* accounts for the largest proportion of identified animal remains. Small bones belonging primarily to the broad toothed rat (*Mastacomys fuscus*), but also including an immature native cat (*Dasyurus viverrinus*) and a bandicoot (*Perameles* sp.), probably represent the disgorged crop contents from owls (e.g. *Tyto novahollandae*). The remains of a sooty shearwater (*Puffinus griseus*) recovered from previously described material (Goede and Murray 1977) may have been picked up on the coast by humans and carried to the cave as an ornament or as food (Van Tets 1977). Alternatively it may have been the victim of owl predation. Petrels, murrelets and shearwaters are regular prey of barn owls off the California coast (Banks 1965; P. Walker, personal communication), and shearwaters regularly fly off course in Tasmania where they could be subject to predation by the masked owl. A single cuboid (M4199-2) represents a large macropodid belonging to the genus *Macropus* and resembling *M. giganteus* in morphology. The specimen is, howvere, larger than any *M. giganteus* in the collection and may represent *M. titan* (Fig. 8, A-C). It perfectly fits a very large metatarsal IV of a specimen assigned to *M. titan* from nearby Titan's Shelter (JF-97) (Goede and Murray 1979). At least two individuals of the pademelon (*Thylogale billardieri*) are also represented.

The fossil material from the three sub-units shows no difference with regard to condition, preservation or species composition. However, the greatest concentration of bone (75%; Table 2) as well as the largest percentage of stone artifacts (80%) came from sub-unit B.

Most of the larger animal bone is in the form of sinuous fragments with sharp, bevelled edges. These breaks probably occurred when the bone was fresh. Stout elements such as

Table 2. *Minimum number of individuals from Site P, sub-unit B.*

Species	MNI
Macropus cf. *titan*	1
Macropus rufogriseus	7
Thylogale billardieri	2
Perameles sp.	1
Dasyurus viverrinus	1
Mastacomys fuscus	16

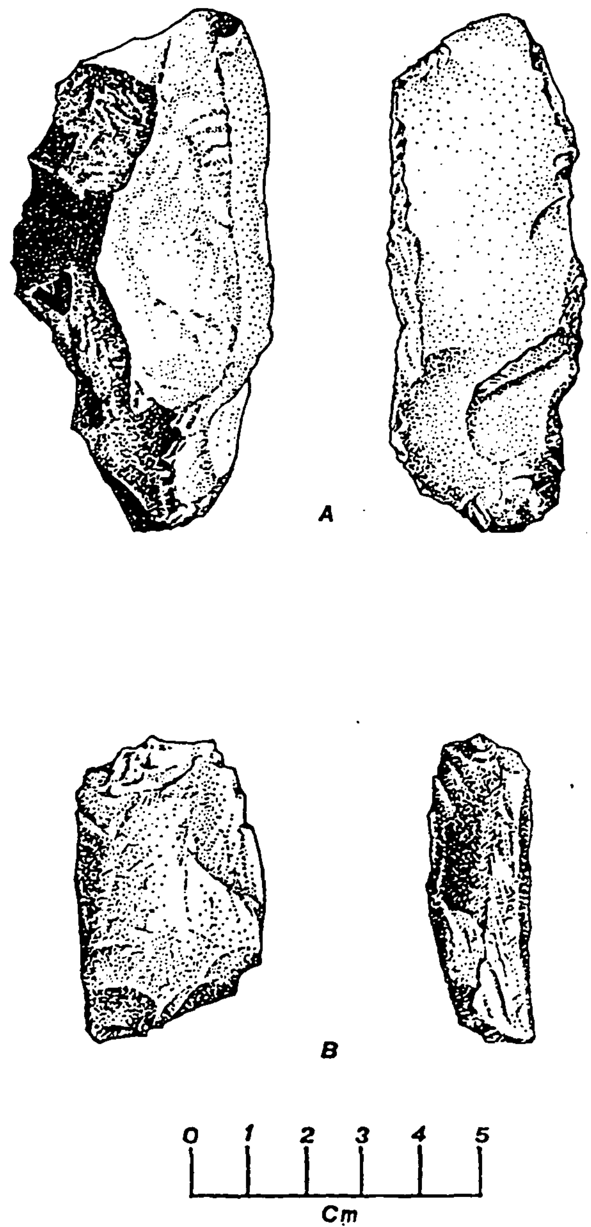

Figure 7. Artifacts from site P.

phalanges and fourth metatarsals of *M. rufogriseus* show similar breaks. Marks attributable to the teeth of carnivorous marsupials (*Sarcophilus harrisii, Thylacinus cynocephalus*) appear to be absent. Rodent tooth marks are present on a few specimens. A small number of bone fragments are burned, and these range in colour from white to black. The white, calcined bone fragments were probably subjected to very high temperatures which would suggest that they had been burned within a fire lens. Long, narrow cuts probably attributable to a stone artifact are present on the distal end of a left humerus of *M.*

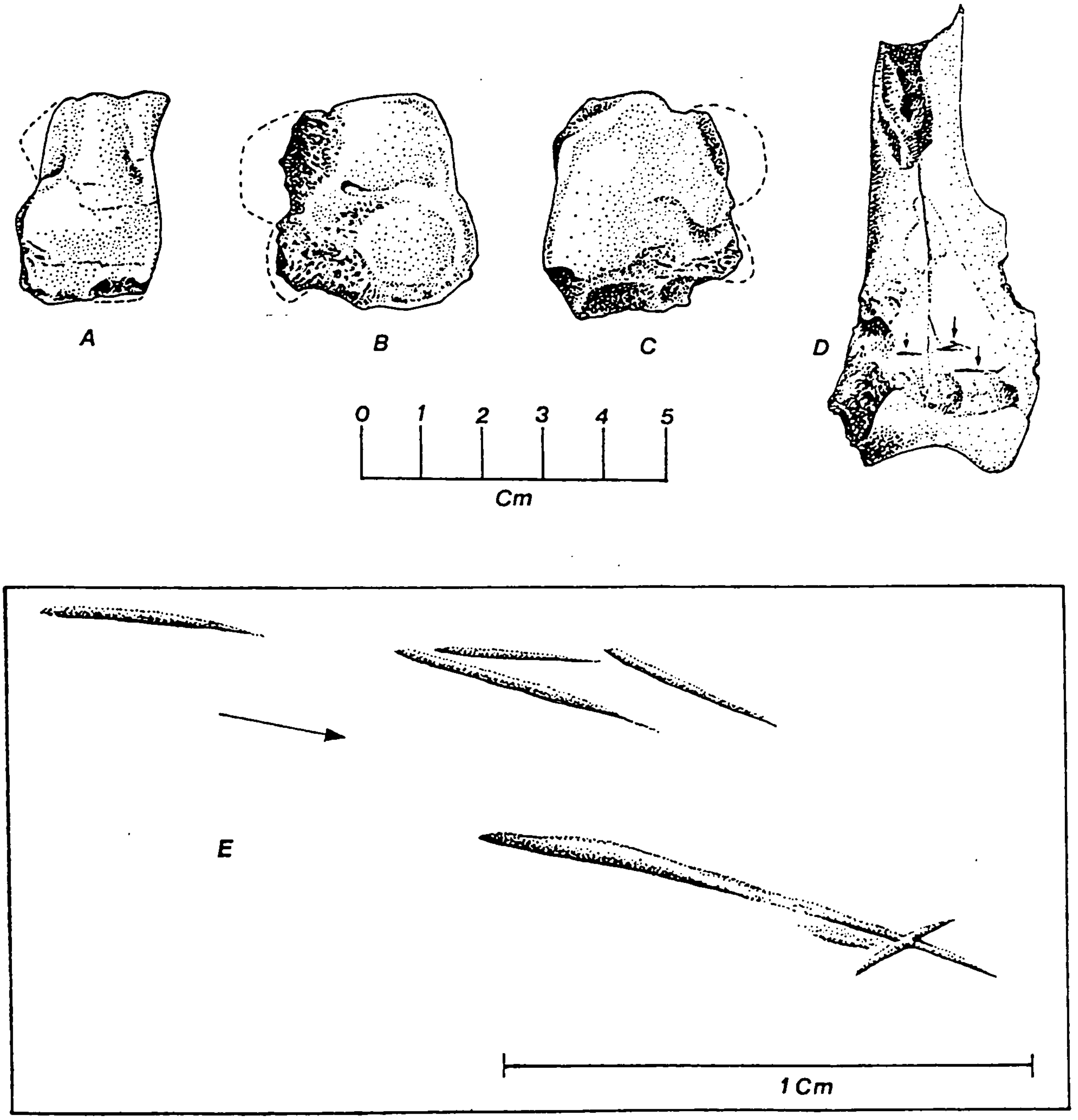

Figure 8. Left cuboid bone of *Macropus* cf. *titan* from site P, sub-unit B (A: dorsal view, B: proximal view, C: distal view. D, left humerus fragment of *Macropus rufogriseus* with cut marks on distal end indicated by arrows. E, drawing of cut marks enlarged 10x (arrow indicates inferred direction of cutting).

rufogriseus (M4199-1) (Fig. 8D, E). These marks are unlike any marsupial carnivore tooth marks known and are more comparable to the sort of scratches whch would be produced by a stone flake on fresh bone. Markings are absent on the posterior side of the specimen where additional tooth marks would be expected to be present if a carnivore were responsible. The presence of articulated manus and pes elements indicates that some agency carried either whole or partial carcasses into the cave. Marsupial carnivores do, of course, drag whole or partially intact corpses into their dens, but subsequently they usually disarticulate them. These articulated elements show no signs of being chewed and are considered consistent with discarded material which had been regarded as inedible by humans.

The nature of the fossil remains of the larger animals is more consistent with their derivation from food remains of humans rather than marsupial carnivores. Remains attributable to carnivore activity have been recovered in nearby caves. These differ from the Beginners Luck Cave site P material in having clear signs of being chewed (epiphyses gnawed off, processes and thin boney flanges chewed away, numerous tooth marks present) and by the lack of other evidence (bones are disarticulated, not burned, large metatarsals are chewed but not broken) (Goede and Murray 1979).

Dating

Prior to the latest excavations the dating of human occupation at site P depended on a single ^{14}C date obtained from charcoal fragments scattered throughout the breccia unit. The age estimate of 12,600±200 years BP (R5001/4, NZ) was obtained by processing without pre-treatment, and the authors have previously expressed the opinion that it represented only a minimum age of human occupation at this site (Goede and Murray 1977). Also reported was a ^{14}C date on organic carbon residue from bone belonging to *Sthenurus occidentalis* collected from another site within Beginners Luck Cave (site M) which indicated an age of 14,450±250 years BP (R5001/3, NZ). There is no archaeological evidence at this site (Goede, Murray and Harmon 1978).

By collecting charcoal separately from each of the three sub-units it was hoped to obtain material for three ^{14}C dates in stratigraphic order. Unfortunately, only sub-unit B, which contained the bulk of the artifacts, yielded sufficient datable charcoal. The sample was pretreated by boiling 2 N HCl and 2% NaOH solutions to remove any post depositional carbon contamination. It yielded an age of 20,650±1790 years BP (GaK-7081), which is significantly older than the previously reported date for this site.

In addition, aspartic acid racemization dating was carried out by Bada on bone material from both sites P and M. This technique has the advantage that it uses much smaller quantities of bone than ^{14}C dating, but its own limitations must be kept firmly in mind as well (Bada and Protsch 1973; Davies and Treloar 1977; Masters and Bada 1978). Application of the technique requires a calibration sample which, when dating Upper Pleistocene deposits, should preferably have an age of approximately 17,000 to 25,000 years BP (Bada and Deems 1975). Such a sample was provided by Bowdler from her ex-excavations in Cave Bay Cave on Hunter Island off the north-western coast of Tasmania. This calibration sample (a macropodid long bone fragment) came from the lowest occupation horizon there which had been dated on associated charcoal at 22,750±420 BP (ANU-1498) (Bowdler 1975, 1977). The reliability of this date is enhanced by the fact that it is one of a sequence of four dates between 14,000 and 23,000 years BP with good agreement between the stratigraphic and chronological sequence.

The rate of racemization of aspartic acid is strongly temperature dependent (Bada and Protsch 1973; Bada and Schroeder 1975). The calibration sample is required in order to estimate the average temperature depression during the last glacial event. This and the subsequent sample were processed as described by Bada and Protsch (1973) and Masters and Bada (1978). The Cave Bay sample (AG21) was found to have a D/L aspartic acid ratio of 0.16. On the assumption that this bone has been exposed to approximately equal time periods of Holocene and Late Pleistocene temperature conditions, it can be deduced that mean annual temperatures during the Late Pleistocene were approximately 6°C lower than at present (see Schroeder and Bada 1973, McCullough and Smith 1976, for the equations used in these calculations).

In order for the bone sample from Cave Bay Cave to be a suitable calibration sample for dating the bones from Beginners Luck Cave, the temperatures of the two sites should be similar. Otherwise the calibration rate constant must be adjusted to the appropriate temperature. The present mean annual temperature at Cave Bay Cave is estimated to be 12°C, whereas based on spot temperature readings, the temperature at Beginners Luck Cave is estimated to be ~8°C. Therefore the Cave Bay Cave calibration rate constant has been adjusted to 8°C using the procedures given by Bada, Schroeder and Carter (1974). Since an adjusted rate constant had to be used, the aspartic acid racemization dates from Beginners Luck Cave should be regarded as preliminary estimates only. Analysis of a sample from site P (AG20), collected before systematic excavation, yielded a D/L aspartic acid ratio of 0.11 and an aspartic acid age of 21,000 years BP (see Masters and Bada (1978) for equation used to calculate this age). The age determination is quite close to the ^{14}C date from sub-unit B.

Aspartic acid racemization analysis of a sample at site M (AG19) has yielded a D/L aspartic acid ratio of ~ 0.2 and an age of ~ 80,000 yers BP. This is an approximate age as only a small amount of aspartic acid was isolated and the measured D/L ratio is thus somewhat uncertain. However, it suggests a much greater age than was previously suggested by the ^{14}C date on organic carbon residue from another bone (14,450±250 years BP).

Re-examination of site M has revealed that contrary to the opinion expressed earlier by two of the authors (Goede and Murray 1977; Goede, Murray and Harmon 1978), the bone material may well have been buried by subsequent sedimentation. The chamber containing this site was almost completely filled with fine-grained alluvial sediments believed to be equivalent in time to the lower unit at site P. It now appears that the bones were originally either embedded within this deposit or accumulated on the depositional surface created by the deposit. They were then lowered to their present position by erosion of the alluvial fill. Burial may have affected the reliability of the bone for ^{14}C dating, and it would now appear prudent to regard the ^{14}C date as a minimum date. The aspartic acid recemization date is therefore thought more likely to give an approximate indication of the true age of the material.

Discussion

The excavations and additional dates from site P now indicate that Aboriginal people were present in the Florentine Valley some 20,000 years ago when Tasmania was a peninsula of the Australian mainland and when the Last Glacial was reaching its climax. Cirque and short valley glaciers would have been present on the Mount Field plateau to the south-east. One valley glacier originating in the Lake Hayes cirque to the east of Mount Field West (1434 m) flowed down the Lawrence Rivulet valley towards the Florentine River. Dolerite outwash gravels were deposited on the floor of the Florentine Valley only three kilometres south of the site. It would now seem that despite the severe conditions the early inhabitants were clearly using the animal resources of the interior at least on a seasonal basis. Information from other cave sites in the Florentine Valley (Goede and Murray 1979) indicates the presence of a varied marsupial fauna in an open environment during the Late Pleistocene.

The Beginners Luck Cave site may represent a bivouac for small bands using the broad Florentine Valley as a route between the upper Derwent River and the wide valleys of the South West (Fig. 1). Whether larger open-air campsites were established remains uncertain. Movement through the valley would have been easy at a time when vegetation was relatively open (Macphail 1975; Colhoun 1978). Under the colder and drier conditions then prevailing, the limestone soils would have supported a productive grassland and herb-field vegetation interspersed with alpine shrubbery.

A belief that Pleistocene humans in Tasmania were confined to the coastal margins and were strongly dependent on littoral food resources appears to have grown up to explain the apparent lack of inland Pleistocene sites (Jones 1968; Bowdler 1977). The new evidence concerning the age of the Beginners Luck site also tends to refute the thoughts so eloquently expressed by Jones (1977:338) that 'The Beginners Luck site does however show the dynamism of opportunity which sometimes accompanies environmental change . . . Between the melting of the periglacial uplands and their filling with dense and non-burnable rainforest, lay a moving phase of exploitable open hunting ground'.

The presence of cherty hornfels from several different sources in the site P fill suggests an established knowledge of stone resources by 20,000 years ago. Further, the site appears to have been used over a relatively long period of time judging from the vertical distribution of artifacts and their relatively large number within the small area excavated.

By 20,000 years BP bands utilizing the valley may have occupied the region bounded on the west by the Gordon River drainage system, to the north and east by the Derwent River and to the south by the Huon River. Movement to the coast could follow any of these large systems, but the Derwent Valley seems most probable on geographic grounds. At present we cannot say whether these bands utilized coastal resources in the same manner or to the same extent as Holocene Tasmanians. Reliance on coastal resources may not have taken place until important resource areas in the interior of Tasmania were modified by changes in the vegetation. Forestation of the river valleys would have greatly reduced the mobility of hunting bands and decreased the grazing range for larger marsupials. The resultant increase in habitat partitioning and geographic complexity may have set the stage for a new adaptive strategy.

Early post-glacial occupations may have centred around the estuaries of the larger river systems making an adaptive transition from open country hunting and gathering to eclectic littoral hunting and gathering. Stabilization of marine resources may not have occurred until the maximum post-glacial sea level was attained. Incipient marine littoral adaptations may be anticipated a few millennia prior to this in the earliest Holocene or latest Pleistocene c. 12-10,000 years ago. Indeed the earliest phases of occupation at Rocky Cape suggest that a less refined, eclectic marine littoral exploitation of approximately 8,000 years ago preceded a more specialized use of resources by mid to late Holocene times (Jones 1968).

Unfortunately no radiometrically dated Pleistocene sites have been located in the eastern half of the state. Sigleo and Colhoun (1975) have shown on stratigraphic grounds that humans were probably present at Old Beach in the lower Derwent Valley between about 20,000 and 10,000 years ago, but the site unfortunately contains no datable material. Possible evidence of Pleistocene occupation in north-eastern Tasmania consists of a single flake recovered from alluvial deposits in the Doone tin mine near Gladstone (David 1923). Occupation is also recorded for the late Pleistocene or early Holocene in the Tamar Valley at Flowery Gully Cave (Gill 1968). We consider the apparent scarcity of early sites in the eastern part of Tasmania to be largely due to the absence of limestone caves as well as to the very limited survey work done to date. However, there may be a real scarcity of sites in the eastern regions due to the occurrence of extremely dry and cold climatic conditions corresponding in time to the glacial maximum (Colhoun 1978), though this suggestion implies, perhaps incorrectly, the notion that the hunter-gatherers of the region were not well adapted at that time.

The new evidence and dates require some revision concerning the coexistence of Pleistocene humans and megafauna in the valley as expressed by Goede, Murray and Harmon (1978). From site P we now have direct evidence of the presence of *Macropus* cf. *titan* at the time of human occupation. On the other hand the *Sthenurus* remains at site M appear to be significantly older. However, the late survival of *Sthenurus occidentalis* and *Macropus titan* has recently been demonstrated in nearby Titans Shelter (JF-97), where both are represented at site F in cave colluvium which must be younger than 20,000 years BP (Goede and Murray 1979).

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Figures 1 to 5 were drawn by Mrs Kate Morris and figures 6 to 8 were drawn by Murray. The manuscript was typed by Mrs Terese Hughes.

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VARIATION IN HARDNESS OF CAVE DRIPS AT TWO TASMANIAN SITES

Albert Goede

Abstract

Thirteen consecutive monthly samples were collected from two drip sites at each of two Tasmanian caves: Little Trimmer at Mole Creek and Frankcombe Cave in the Florentine Valley. At one of the two drip sites in Little Trimmer a positive relationship was found between the logarithm of precipitation and the total hardness without any detectable lag effect. No such relationship was detected at the other drip site despite its close proximity. At both drip sites the hardness values fail to show a seasonal pattern and are clearly unrelated to surface temperature variations. In strong contrast both drip sites in Frankcombe Cave showed significant seasonal variation and close positive correlation with mean monthly temperature with lag times of one and two months respectively. At one of the two drip sites the influence of monthly precipitation on variations in drip hardness could also be detected. The strong temperature dependence of cave drip hardness values at these sites may well be due to soil exposure to direct insolation following recent clear-felling and burning of the vegetation in the area.

INTRODUCTION

A programme of sampling has been carried out in two caves in different major Tasmanian karst areas, Little Trimmer at Mole Creek and Frankcombe Cave in the Florentine Valley (Figure 1). Two drip sites were sampled monthly in each cave over a period of thirteen months. Few studies of this kind have been previously described. Pitty (1966) made monthly measurements of water hardness at a number of seepage points in Poole's Cavern, Buxton, Derbyshire in England. Using the statistical method of partial correlation coefficients he was able to show significant relationship between drip hardness on the one hand and the climate elements of temperature and precipitation on the other, especially when lag effects were taken into account. He also considered the possible causal relationships between climatic and climate-controlled factors and water hardness.

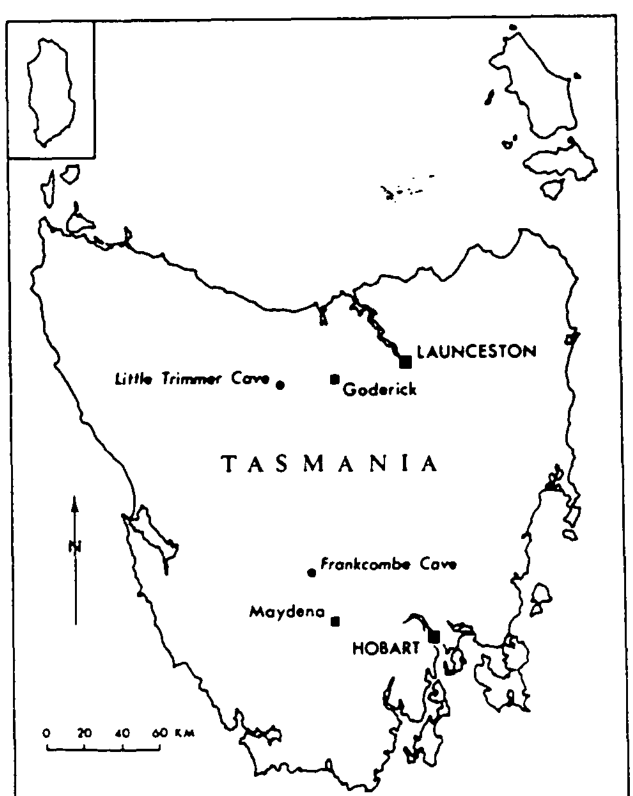

Figure 1 - Location map of cave sites and nearest climatic stations.

Jennings (1979) carried out a similar monthly sampling programme for two years in Murray Cave, Cooleman Plain, Australia but also made measurements of CO_2 in the cave atmosphere and in the soil above the cave. However, he found that "lagged correlation on a weekly and 3 weekly basis of individual drip hardness on air temperature and precipitation yielded few significant results". He concluded that there was only a weak case for dominance of hardness by temperature through rhizosphere CO_2 and no evidence which would support the hypothesis of dominance of antecedent precipitation.

In the present work, precipitation data was measured at surface sites in close proximity to each cave entrance. At each of the two sites a monthly raingauge was installed and visited monthly as close as possible to the middle of the month. Temperatures were not measured at the surface sites but were calculated from mean monthly temperatures at the two nearest meteorological stations of Goderick (near Deloraine) and Maydena (Figure 1). For further information see Goede, Green & Harmon (in press). Details of the cave sites and nearest meteorological stations are given in Table 1. Data for the stations were obtained from 'Climatic Averages Australia' (Bureau of Meteorology, 1975). Sample collections from both surface and underground sites were made monthly for a period of thirteen months from December 1978 to December, 1979).

Both caves are developed in Gordon Limestone of Ordovician age and the hills in which they are located are composed entirely of this rock.

TABLE 1 Details of cave sites and nearest meteorological stations

Site	Longitude	Latitude	Altitude (m)	Mean Annual Temp (°C)	Mean Annual Prec. (mm)
*Little Trimmer Cave, Mole Creek	146°15'E	41°34'S	460	9.2**	-
Goderick, Deloraine	146°38'E	41°31'S	253	10.7	1061
*Frankcombe Cave Florentine Valley	146°27'E	42°32'S	400	9.2**	-
Maydena	146°36'E	42°46'S	267	10.2	1230

* Sites where monthly precipitation samples were collected
** Estimated from nearest meteorological station.

METHODS

In each of the two caves two drip sites were selected in close proximity to each other. In Little Trimmer they were approximately 2 metres apart and in Frankcombe Cave approximately 10 metres. At each drip site a 21 cm diameter plastic funnel was installed and connected by means of a 2 cm diameter hose to a 25 litre container. On each monthly visit water samples were collected in polythene bottles which were completely filled and sealed on the spot. Calcium and total hardness were determined in the laboratory by titration with EDTA as soon as possible after collection (Douglas, 1968). At the time of analysis specific conductivity was also measured. It had originally been intended to accumulate all drip waters between visits but drip rates proved to be more rapid than anticipated so that the containers frequently overflowed. To minimize the problem of taking a representative sample in this circumstance hoses were inserted deep into the containers so that any water would have mixed thoroughly with the contents before it overflowed. This probably caused some bias in hardness values towards the latter part of the sampling period. There are some advantages in obtaining mean hardness values over a period of time rather than the point values of samples collected at wide intervals of time as did Pitty and Jennings. These investigators related the hardnesses to climatic parameters averaged over periods of time of varying lengths.

Instantaneous drip rates were measured during visits from July (Frankcombe Cave) and August (Little Trimmer) onwards. Maximum and minimum instantaneous drip rates recorded for the four sites were

Little Trimmer:	S_1	.008 - 1.758	litres/hour
	S_2	.612 -17.393	litres/hour
Frankcombe Cave:	S_1	.031 - 3.823	litres/hour
	S_2	.287 - 6.040	litres/hour

The principal purpose of the monthly sampling programme was to collect precipitation and seepage waters for isotopic analysis of $^{18}O/^{16}O$ and D/H ratios and to relate these measurements to the isotopic composition of actively forming speleothems (Goede, Green & Harmon, in press). To this end monthly air temperature measurements were also taken at the cave drip sites. Little Trimmer was found to have a mean annual temperature of 9.5°C with a range of 1.2°C and Frankcombe Cave a mean annual temperature of 8.3°C with a range of 0.3°C.

DRIP HARDNESS

As might be expected, calcium and total hardness are very closely related at all four drip sites (Figures 2 and 3). Mean values of the sites are as follows:

		Total Hardness (p.p.m.) Mean		S.D.	No. of Observations
Little Trimmer Cave (Mole Creek)	S_1	231	±	43.3	13
	S_2	308	±	17.9	12
Frankcombe Cave (Florentine Valley)	S_1	198	±	18.6	13
	S_2	211	±	15.5	12

Little Trimmer

The two drip sites are only 2 metres apart but differ markedly in their mean total hardness values and their degree of variability (Figure 2). Applying Student's t test the difference between the means is found to be highly significant ($p <<< .001$). In order to determine the extent to which total hardness variations at the two drip sites are related, correlation analysis was carried out ($r = .60$, $p < .05$). Only 36% of the variation in one drip is statistically 'explained' in terms of the other.

When mean monthly hardness (H_{S1}) for drip site S_1 are graphed against monthly precipitation amounts (P_m) for the same periods (Figure 4) a non-linear relationship is found which is best represented by the equation

$$H_{S1} = 225.02 \log P_m - 222.91 \quad (r = .68) \qquad (1)$$

This positive relationship is significant ($p = .01$) and indicates that nearly half (45.9%) of the variations in drip hardness at S_1 can be attributed to variation in precipitation amounts during the same monthly periods. Residual values do not shown any relationship to mean monthly surface temperature.

Investigating the same type of relationship for drip site S_2 no significant correlation exists ($r = .27$, $p >> .20$). Total hardness values for S_2 do not exhibit a seasonal trend indicating that they are not related to surface temperature variations.

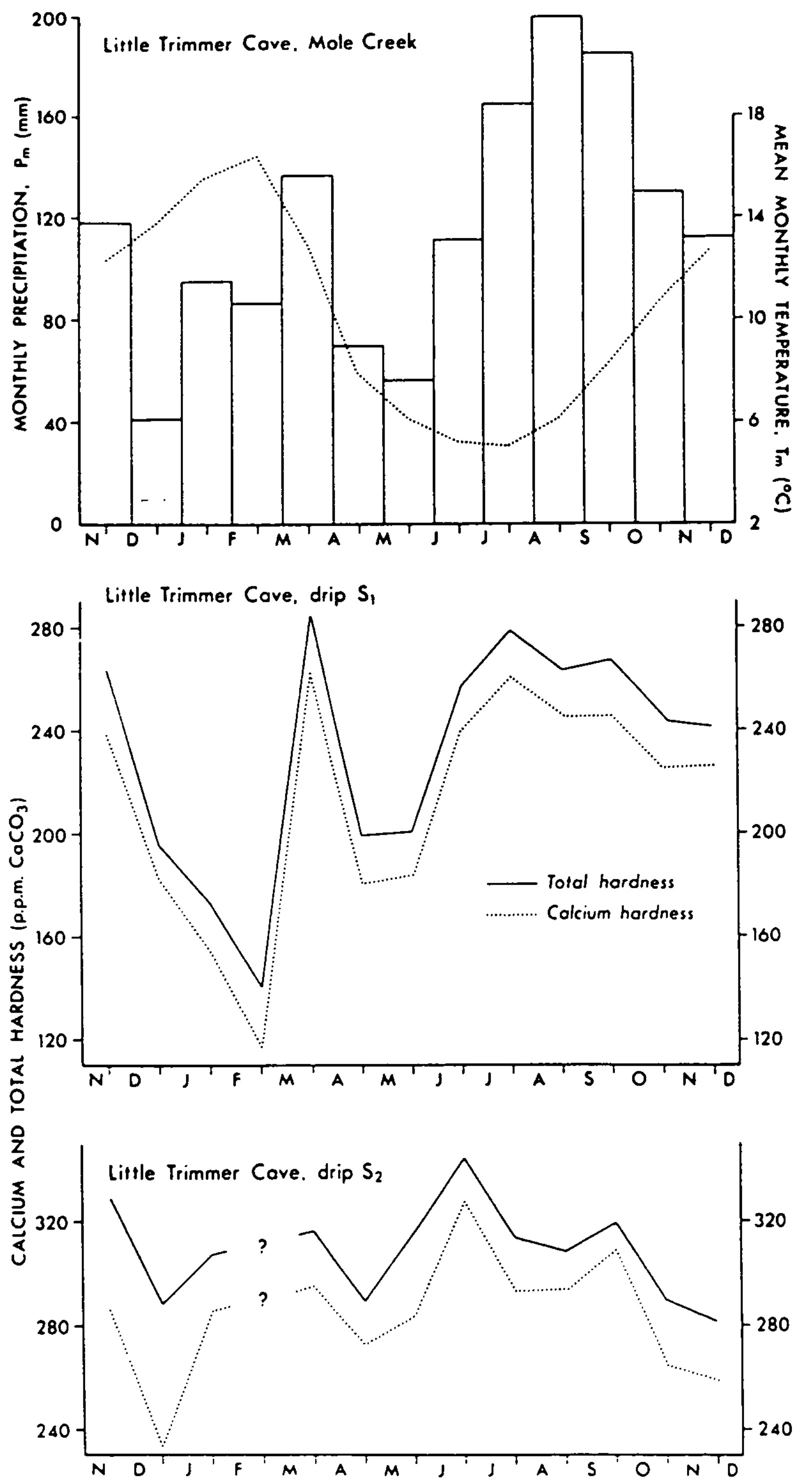

Figure 2 - Monthly precipitation and calculated mean monthly temperature for surface site at Little Trimmer. Monthly total and calcium hardness values for cave drips S_1 and S_2 in the same cave.

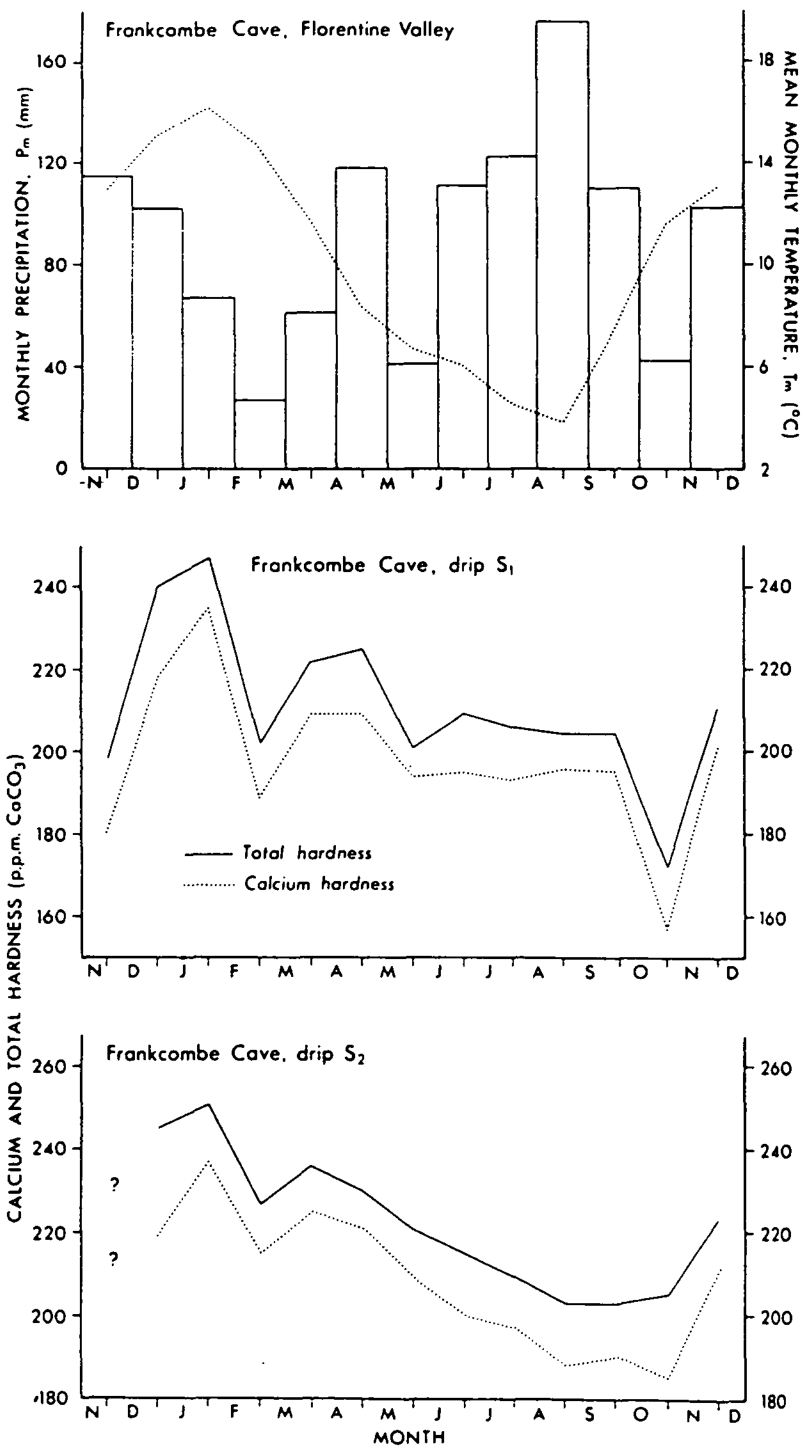

Figure 3 - Monthly precipitation and calculated mean monthly temperature for surface site at Frankcombe Cave. Monthly total and calcium hardness values for cave drips S_1 and S_2 in the same cave.

Frankcombe Cave

The two drip sites are approximately 10 metres apart but show a much greater similarity in monthly total hardness values and their standard deviations than do the two Little Trimmer sites (Figure 3). Using Student's t test a comparison of the two means shows that the difference between them is not statistically significant ($.05 << p < .10$).

Again it appears that hardness variations between the two drip sites are related. Correlation analysis shows a coefficient of .87 ($p << .001$) indicating a highly significant relationship. 75% of the variation in one drip is statistically 'explained' in terms of the other.

When monthly total hardness values for both drip sites are graphed against mean monthly temperatures there is clearly a relationship with a lag effect between the two (Figure 5). With varying lag effects the following positive correlation coefficients are found:

Lag time (months)	Nil	1	2	3
S_1	.361	.479	.586	.427
S_2	.747	.870	.784	-

For S_1 the highest correlation coefficient (.586) is found with a lag period of two months and is significant at the 5% level. For S_2 the highest coefficient (.870) is found with a lag period of one month and is significant at the 0.1% level. The equations to the lines of best fit (reduced major axes) are

$$H_{S1} = 164.86 + 4.70\ T_{m-2} \qquad (2)$$

$$H_{S2} = 185.08 + 3.77\ T_{m-1} \qquad (3)$$

When residual values derived from these two equations are compared with monthly precipitation amounts there appears to be some positive relationship with precipitation amounts for S_1 but little evidence of any relationship for S_2.

To see if the statistical explanation for monthly total hardness values for drip site S_1 could be improved, multiple correlation regression was carried out with T_{m-2} and $\log P_m$ (monthly precipitation) as the independent variables. The following relationship was obtained

$$H_{S1} = 89.73 + 3.76\ T_{m-2} + 44.03 \log P_m$$

The multiple correlation coefficient R = .77 indicates that 59% of the variance is accounted for compared with 34% when only temperature is taken into account.

DISCUSSION

Mean hardness values found in this study are comparable with those reported by Pitty (1966) from Poole's Cavern except for S_2 at Mole Creek which is significantly higher than any of his mean values although it must be remembered that Pitty measured only calcium hardness since magnesium carbonates were claimed to be low or non-existent in his samples.

In contrast Jennings (1979) reports the mean total hardness of drip measurements in Murray Cave as 141.4 p.p.m. for 228 measurements. This compares with 268 p.p.m. for 25 measurements in Little Trimmer and 204 p.p.m. for 25 measurements in Frankcombe Cave. It is interesting to note that in both caves it is the drip with the greater rate of flow which has the greater hardness values.

At the Tasmanian sites the natural vegetation of wet sclerophyll forest is more vigorous and has a much greater biomass than the subalpine grassland at Cooleman Plain. Since the provenance of soil CO_2 is predominantly biogenic it is expectable that the Tasmanian sites would yield much higher hardness values than Murray Cave.

Little Trimmer

As mentioned earlier a significant positive relationship is found when total hardness values of cave drip S_1 are correlated with the logarithm of monthly precipitation. It is clear that the response of total hardness to precipitation is a rapid one with no detectable lag effect.

Pitty (1966) tabulates eleven factors which could cause differences in the quantities of carbonates dissolved in karst water. Five of these are controlled by precipitation and three can be expected to have a positive correlation with carbonate hardness. They are:

1) Increased precipitation causing an increase in biotic activity.
2) Greater solution with faster flow.
3) Greater solution with increased pressure.

Factor 1) cannot apply in the case of S_1 because firstly it would take time for the increased moisture to boost the carbon dioxide concentration in the soil and secondly time is also required for the soil water to take up carbonate and move down to the roof of the cavern. Goede, Green & Harmon (in press) using monthly measurements of the deuterium-hydrogen ratio of both precipitation and S_1 seepage have shown that the average time taken by the water to reach the S_1 seepage point after falling as precipitation is approximately 2 months.

Clearly factors 2) and 3) are more plausible mechanisms because their effects would be felt much more rapidly. However, one might have expected them to be more effective with higher precipitation amounts much in excess of those required to saturate the soil. In contrast the evidence shows that total hardness values respond most strongly when monthly precipitation amounts are small.

Another possibility that must now be considered is 4) that more loss of carbon dioxide, hence more deposition of calcium carbonate per unit volume of water occurs when the rate of cave drip is low since

a) it makes more time available for these processes to operate before the drip falls.
b) there will be greater surface area of contact with both the depositional surface and the **cave atmosphere.**

Clearly the drip rate of S_1 is highly variable and much lower than S_2.

As pointed out, drip S_2 has little similarity with S_1 in terms of its temporal pattern of hardness variation. The S_2 pattern suggests a weak positive correlation with monthly precipitation and a weak negative one with mean monthly temperature but neither approaches statistical significance. The minima in December-January and April-May seem to correlate with similar minima in the graph for S_1 and probably indicate periods of moisture deficiency. The third minimum from July to September is weakly represented in the S_1 graph and probably indicate periods of moisture deficiency. The third minimum from July to September is weakly represented in the S_1 graph and may reflect an excess of water causing saturation of the soil. Figure 4 also hints at a possible fall in hardness when mean monthly precipitation amounts exceed 140 mm. Most likely the S_2 pattern represents the complex interaction of a number of factors relating to both temperature and precipitation.

Frankcombe Cave

The presentation of data and analysis of results are shown graphically in Figures 3 and 5. Hardness variations at the two drip sites are much more closely related to each other and both appear to be predominantly controlled by a temperature related factor with a lag time from one to two months showing a positive relationship with hardness.

Pitty (1966) listed six factors which are temperature controlled. Out of the six, four could apply to the Florentine Valley and of these only two would lead to a positive relationship between carbonate hardness and temperature. They are

1) greater output of carbon dioxide with increased biotic activity at higher temperatures
2) gain in soil carbon dioxide with photosynthesis due to increased root respiration.

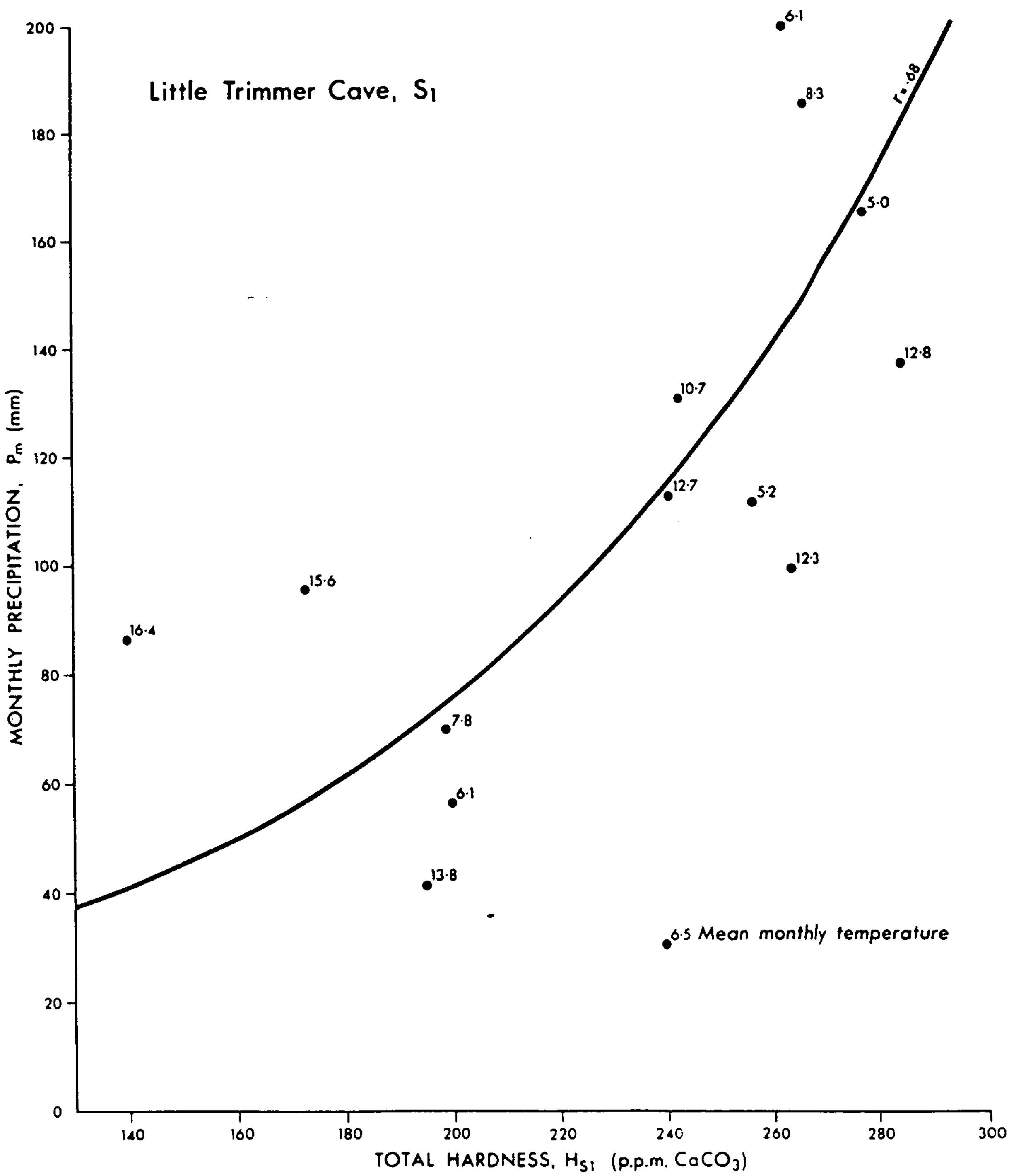

Figure 4 - Relationship between total hardness and monthly precipitation for drip site S_1 in Little Trimmer.

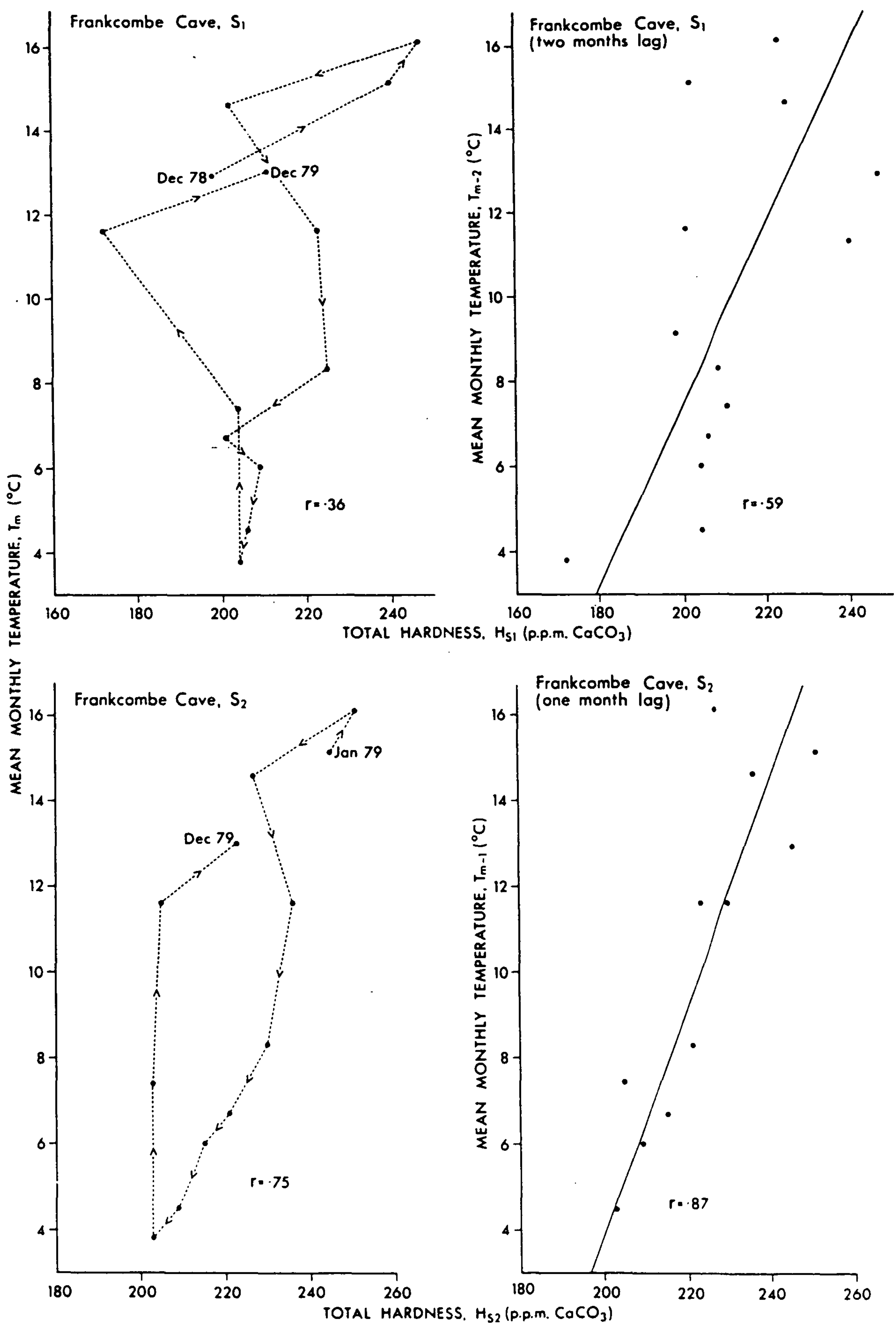

Figure 5 - Relationships between total hardness and mean monthly temperature illustrating lag effects for drip sites S_1 and S_2 in Frankcombe Cave.

These two factors cannot really be separated as increased plant activity is likely to encourage greater biotic activity of the soil fauna and flora. The two factors together, acting under the control of temperature, appear to be responsible for the positive relationship between mean monthly temperature and hardness with the observed lag effect.

Jennings (1979) has put forward another possible temperature-controlled factor

3) the evaporative concentration of the soil water solutions by high temperatures.

This is unlikely to be a major factor here although it may have contributed to the pronounced January-February hardness peak in both the S_1 and S_2 curves.

Superimposed on the overall temperature control of hardness at S_1 the graph shows three pronounced minima clearly coinciding with the three driest months so there appears no doubt that moisture deficiency plays a role in depressing the hardness values, while excess moisture appears to have little effect. Again, for reasons already outlined in the Little Trimmer section we find that the absence of a significant lag effect and the dominant influence of small precipitation amounts points to rapid loss of calcium carbonate by deposition in the cave environment when the rate of flow of the cave drip is low.

The level of explanation of hardness variations at S_1 has been shown to improve significantly when both mean monthly temperature and the logarithm of mean monthly precipitation are taken into account.

At S_2 only one of the three hardness minima attributed to moisture deficiency in the S_1 graph appears to be present and that is the late summer one in February-March. This is probably due to the fact that it has a faster drip rate.

CONCLUSIONS

At none of the four sites examined does the availability of moisture appear to be a significant control on the concentration of carbon dioxide in the soil. Where precipitation amounts do appear to influence the drip hardness as it does predominantly at the S_1 site in Little Trimmer and partly at the S_1 site in Frankcombe Cave it appears to do so indirectly. The factor appears to be rapid lowering of calcium carbonate content by deposition when drip rates are very low.

While it is dangerous to draw sweeping conclusions on the basis of only four cave drip sites it is interesting to compare the mean drip rates with the degree of influence of precipitation on hardness variation

		Mean drip rates (litres/hour)	Influence of precipitation
Little Trimmer	S_1	.690	dominant
	S_2	8.601	not apparent
Frankcombe Cave	S_1	1.293	significant
	S_2	3.246	slight

Clearly there is a suggestion of an inverse relationship between the mean drip rate and the influence of precipitation.

With respect to temperature, it is obvious that the Frankcombe Cave drips are strongly influenced by temperature with a lag effect of one to two months and that this factor operates by controlling biological activity and hence the level of carbon dioxide in the soil.

The area above Frankcombe Cave was clear-felled and burned a couple of years before the start of measurements and although a partial weed-cover had established itself and regrowth of forest species commenced the soil temperature can be expected to be still strongly influenced by direct insolation. In contrast at Mole Creek the hill above Little Trimmer is covered by mature wet sclerophyll forest that has not been recently burned and has been subject only to selective logging a considerable time ago.

It would be interesting to resume sampling of the Frankcombe Cave drip sites some years from now when forest cover has re-established itself in order to assess the extent to which the behaviour of the cave drips will have changed.

ACKNOWLEDGEMENTS

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ISOTOPIC COMPOSITION OF PRECIPITATION, CAVE DRIPS AND ACTIVELY FORMING SPELEOTHEMS AT THREE TASMANIAN CAVE SITES

10

A. Goede, D.C. Green, R.S. Harmon

Abstract

Monthly samples of precipitation and cave drips were collected from three Tasmanian cave sites along a north-south transect and their $^{18}O/^{16}O$ ratios determined. At one station D/H ratios were also measured and the relationship between $\delta^{18}O$ and δD values investigated. The $^{18}O/^{16}O$ and D/H ratios of monthly precipitation show marked seasonality with values correlating strongly with mean monthly temperatures. The effect of temperature on $^{18}O/^{16}O$ ratios appears to increase as one goes southwards and is at least twice as strong at Hastings (.61°/oo SMOW/°C) as it is at Mole Creek (.28°/oo SMOW/°C).

Irregularities in the seasonal pattern of $^{18}O/^{16}O$ change are particularly pronounced at Hastings and in the Florentine Valley and can be attributed to the amount effect. For $\delta^{18}O$ values $>$ -5.5°/oo the combined data from the three Tasmanian stations show an amount effect of .026°/oo SMOW/mm.

Cave drips show apparently random, non-seasonal variation in $^{18}O/^{16}O$ isotopic composition but the weighted mean of the $^{18}O/^{16}O$ isotope composition of precipitation provides a good approximation to their mean $^{18}O/^{16}O$ isotopic composition. In contrast the D/H ratios for a cave drip site in Little Trimmer Cave, Mole Creek, show a distinct seasonal pattern.

The $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios have been determined for a number of actively forming speleothems. With respect to $^{18}O/^{16}O$ it is found that speleothems at the three sites are being deposited under conditions approaching isotopic equilibrium. The $^{13}C/^{12}C$ ratios of these speleothems are highly variable but the generally less negative values found in Frankcombe Cave (Florentine Valley) compared with the other two sites may reflect the effects of recent clear felling in the area.

METHODS

Three pairs of surface and underground sample sites were selected. The sites were chosen along a north-south transect and located in karst areas likely to provide speleothem material suitable for yielding palaeoenvironmental information from isotopic analyses (Figure 1). At each surface site a monthly raingauge was installed while at each cave site plastic funnels connected to containers were placed under two cave drips in close proximity. In addition a set of sheathed maximum and minimum thermometers (Dobros, nos. 1001 and 1002), mounted on a wooden board, was located close to the cave drip collectors. At Mole Creek and in the Florentine Valley the surface site was located in close proximity to the cave entrance. At Hastings, because of the dense forest at the cave site, the monthly raingauge was installed at The Chalet approximately 3 km SSE of the cave and at a significantly lower elevation. The site has the advantage of a meteorological station so that daily precipitation and temperature data are available for the period of record. Table I gives details of the three cave sites and the nearest meteorological stations.

All sites were visited monthly as close as possible to the middle of the month. These visits commenced in December 1978 for the Mole Creek and Florentine Valley sites and in January 1979 for Hastings. At all three sites they continued for the whole of 1979. At each surface site the accumulated precipitation was measured and water samples collected for $\delta^{18}O$ and δD isotopic analysis. At underground sites the actual, minimum and maximum temperatures were read and the thermometers reset during each visit. Water samples were collected from cave drips for $\delta^{18}O$ analysis as well as analysis of calcium and total hardness. The analysis of hardness variations in cave drips is reported in another paper (Goede, 1981). Samples were also collected for δD analysis at one of the two cave drip sites at each of the three localities. δD samples for precipitation and seepage have so far been analysed only for the Mole Creek station.

Isotopic analyses of precipitation and seepage samples for $\delta^{18}O$ were made using a VG Micromass 602D mass spectrometer. Isotopic analyses for δD were carried out at the Scottish Universities Research and Reactor Centre at East Kilbride.

Some problems were encountered during collection of the data. The maximum thermometer installed in King George V Cave, Hastings, proved to be unreliable and its readings have been excluded from consideration. It had originally been intended to accumulate all drip waters between visits but in the case of Little Trimmer and Frankcombe Caves drip rates proved to be so rapid that the 25 litre containers used frequently overflowed. To reduce the problem of collecting a representative sample in this circumstance hoses were inserted deep into the containers to allow thorough mixing of the contents before they overflowed. Instantaneous drip rates, obtained by timing drip water accumulation over a short time period, were measured from July (Frankcombe Cave) and August (Little Trimmer) onwards.

At Hastings problems of overflowing did not arise but both drip sites dried up progressively during the period of sampling due to the long drought which affected south-eastern Tasmania during 1979. At King George V Cave even the spring rainfall maximum which occurred from August to October failed to re-activate the drips because of the unusually dry preceding soil conditions. Therefore it was not possible to collect cave drip samples from this site from July onwards.

ANALYSIS OF OBSERVATIONS

Precipitation patterns

The monthly precipitation totals for the period mid-December 1978 to mid-December 1979 are shown in Figures 2, 3 and 4.

At Mole Creek the driest monthly period was December-January (41 mm) and the wettest, August-September (199 mm) (Figure 2). There was a major rainfall maximum in winter and spring (July-October) and a minor maximum in March-April. Precipitation for the period was 1385 mm which is close to the mean annual precipitation for the area. The record can be regarded as representing a typical year.

In the Florentine Valley the driest monthly period was February-March (27 mm) and the wettest August-September (176 mm) (Figure 3). Precipitation for the period was 1090 mm which was well below the mean annual precipitation for the area estimated to be at least 1500 mm. During the year precipitation was highest in late winter and spring and lowest in late summer.

At Hastings daily rainfall amounts from the meteorological station were available as well as totals form the monthly gauge. The annual precipitation amount at the Bureau of Meteorology station was 1090 mm compared with 976 mm from the monthly gauge (Figure 4). Amounts from the monthly gauge were always slightly below those from the station. Since these differences were no larger during the summer than during the winter they are not due to evaporation from the monthly gauge but appear to have resulted from either local site difference or bias in one or both of the gauges. Both annual amounts were well below the mean annual precipitation of 1367 mm recorded for the station (Bureau of Meteorology, 1975). The graph shows two precipitation maxima; one in March-May and the other in July-October with extremely dry conditions intervening from January to March and May to July.

TABLE I. Details of cave sites and nearest meteorological stations.

Site	Longitude	Latitude	Altitude	Mean Annual Temp. (°C)	Mean Annual Precip. (mm)
* Little Trimmer Cave Mole Creek	146°15'E	41°34'S	460	9.2+	-
Goderick, Deloraine	146°38'E	41°31'S	253	10.7	1061
* Frankcombe Cave, Florentine Valley	146°27'E	42°32'S	400	9.2+	-
Maydena	146°36'E	42°46'S	267	10.2	1230
King George V Cave, Hastings	146°51'E	43°23'S	180	9.9+	-
* The Chalet, Hastings	146°53'E	43°25'S	40	10.9	1367

* Sites where monthly precipitation samples were collected.

+ Estimated from nearest meteorological station.

Isotopic composition of precipitation

The three stations show the pronounced pattern of seasonal variation in the $^{18}O/^{16}O$ ratio characteristic of mid-latitudes, (Figures 2, 3 and 4), and termed the temperature effect by Dansgaard (1964). Precipitation was isotopically heavy during the summer months and isotopically light during the winter months. The Mole Creek record displayed the most regular seasonal pattern although even here the precipitation for December 78 - January 79 was unusually heavy isotopically. It was also a particularly dry month.

The patterns for Hastings and the Florentine Valley were less regular but once again it was not noticeable that isotopically heavy values tended to be characteristic of dry months which tended to be more common at the two stations because of the southeast Tasmanian drought. This phenomenon of variation in isotopic composition depending on the quantity of monthly precipitation has been described as the amount effect by Dansgaard (1964). He has attributed it to the following factors:

(1) Variation in the isotopic composition of newly formed condensate as a result of cooling during the condensation process. The amount of precipitation is related to the amount of cooling.

(2) Fractionation by isotopic exchange between the drops and the environmental vapour through which they fall on the way down.

(3) Evaporation from falling drops where they pass through low humidity air at lower elevations.

All three factors will lead to a negative correlation between $\delta^{18}O$ values and the precipitation amount.

When values of $\delta^{18}O$ for monthly precipitation were plotted against monthly precipitation amounts for all three stations it was found that the amount effect was apparent for $\delta^{18}O$ values > -5.5°/₀₀ (Figure 5). Correlation analysis gave a coeficient of $r = -.65$. Student's t test showed this correlation to be highly significant ($p >> .001$). The equation to the line of best fit (reduced major axis) was determined as:

$$\delta^{18}O = -.0256\ P_m - 1.521 \qquad (1)$$

This indicates that values of $\delta^{18}O$ become isotopically lighter by approximately 1°/₀₀ for every 40 mm increase in monthly precipitation.

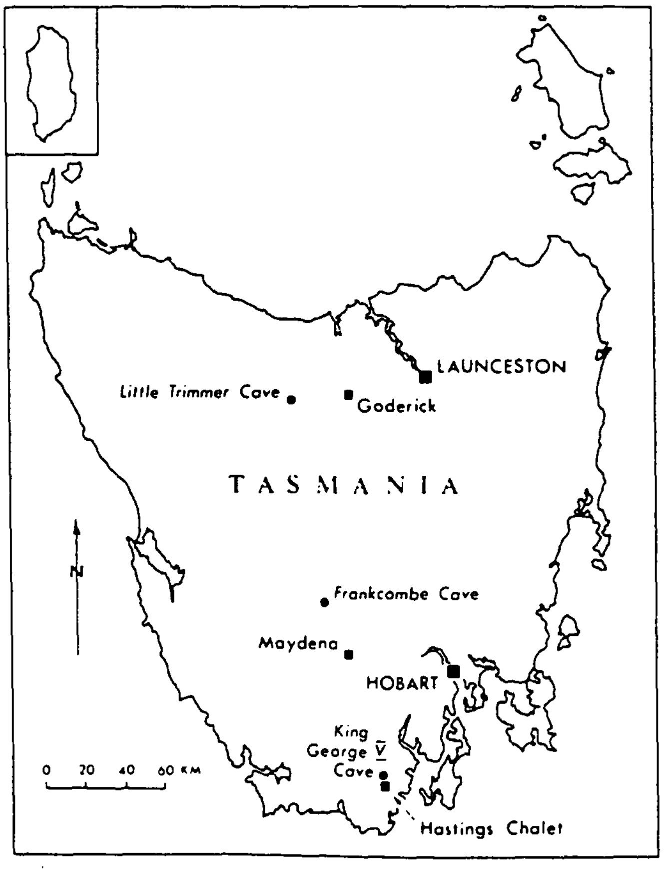

Figure 1. Location map of the cave sites and nearest climatic stations.

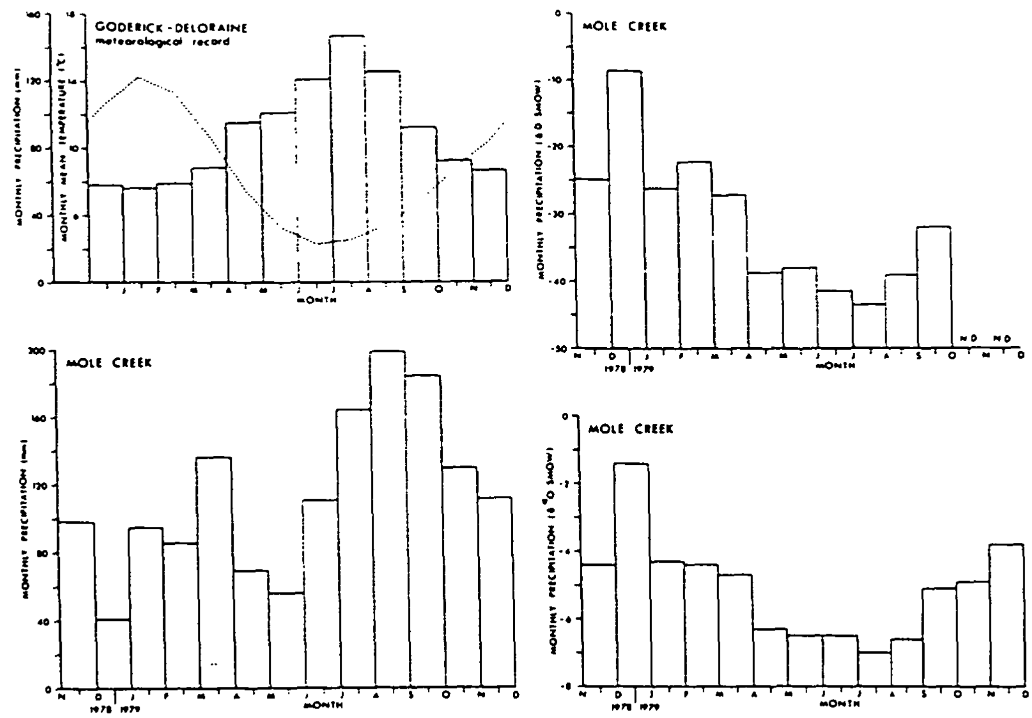

Figure 2. Thirty year meteorological record at Goderick (Deloraine) together with monthly precipitation amounts, δD and $\delta^{18}O$ values for the period December 1978 to December 1979 at Little Trimmer Cave, Mole Creek.

Dansgaard (1964) states that the amount effect is found all the year round at most tropical stations and in the summer time at mid-latitudes. However, it appears that during the drought conditions prevailing in southeastern Tasmania during 1979 the amount effect was noticeable during a few winter months (Figure 5). It appears to explain most of the irregularities in the seasonal pattern found at the Hastings and Florentine Valley stations.

At Mole Creek the D/H ratio (δD value) of monthly precipitation was also measured. The seasonal pattern of variation closely followed that of the $\delta^{18}O$ value. In correlation regression analysis of the two sets of values (Figure 6) the December-January data were excluded because the isotope values were clearly anomalous with respect to the trend. A line of best fit (reduced major axis) is obtained with the equation.

$$\delta D = 6.98\ \delta^{18}O + 5.65 \quad (r = .97) \qquad (2)$$

When comparing mean annual isotopic values between northern hemisphere stations Dansgaard (1964) found that the data fitted best the line $\delta D = 8.1\,\delta^{18}O + 11$ for unweighted means and $\delta D = 8.0\ \delta^{18}O + 10$ for weighted means. The application of t-tests (Silk, 1979) to the sample slope and intercept terms of equation (1) indicates that the slope value of 6.98 is significantly lower than the slope value of 8 at the 10% level and the intercept value is not significantly different from 10. Dansgaard's equation has been used to describe the relationship between δD and $\delta^{18}O$ in fluid inclusions in stalagmites (Schwarcz *et al.*, 1976) in order to arrive at estimates of palaeotemperature. This may not be a valid procedure as it involves consideration of a temporal relationship at one site instead of a spatial relationship at a number of sites. The two relationships need not be identical.

In order to investigate the statistical relationships between monthly isotope values and mean monthly temperatures for the three surface sites it was necessary for two of the sites (Mole Creek and Florentine Valley) to obtain mean monthly temperatures from the nearest meteorological station (Goderick and Maydena). After the field work had been completed it was discovered that temperature measurements at Goderick had ceased at the end of October 1978 and that the Maydena record for the period of sampling was incomplete. Fortunately, it was found that mean monthly temperatures at Goderick correlated very closely with those of the Palmerston station (146°59'E, 41°47'S) and mean monthly temperatures at Maydena correlated very closely with those at Strathgordon (146° 3'E, 42°46'S). The Palmerston data were utilised to synthesize the mean monthly temperature values at Goderick and the Strathgordon data were employed to complete the mean monthly temperature records at Maydena.

Since sampling was done about the middle of each month, corresponding mean monthly temperatures were obtained by taking the average of the two months overlapping the inter-sample period. For Mole Creek and the Florentine Valley the estimates have been corrected for the differences in elevation between the rainfall station and the meteorological station. The correction factor used is $1^{\circ}C/150$ metres (Haltiner & Martin, 1957).

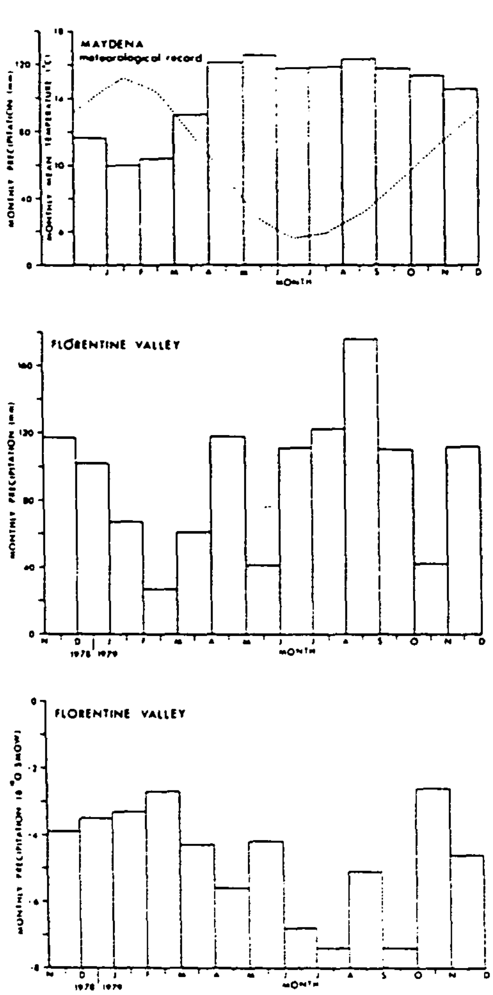

Figure 3. Thirty year meteorological record at Maydena together with monthly precipitation amounts and $\delta^{18}O$ values for the period December 1978 to December 1979 at Frankcombe Cave, Florentine Valley.

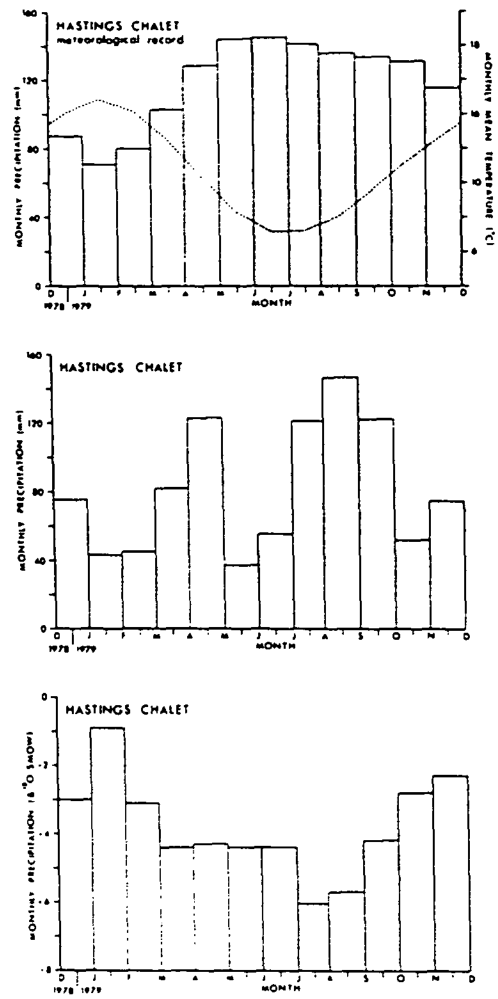

Figure 4. Thirty year meteorological record at Hastings Chalet together with monthly precipitation and $\delta^{18}O$ values for the period January 1979 to December 1979.

Regression analysis was carried out to relate $\delta^{18}O$ and δD values to mean monthly temperatures (T_m) for the three rainfall stations (Figure 7). Equations to the reduced major axes are:

Mole Creek: $\delta^{18}O = .28T_m - 8.13$ (r=.91) (3)

$\delta D = 1.78T_m - 50.4$ (r = .95) (4)

Florentine Valley: $\delta^{18}O = .39T_m - 8.78$ (r = .76) (5)

Hastings: $\delta^{18}O = .61T_m - 10.13$ (r = .86) (6)

In the analyses the Mole Creek data for December-January were again excluded because the isotope values were anomalous with respect to the trend. The temperature coefficients (slope values in the above equations) increase as one goes further south and this could well be due to the increased amount effect resulting from the unusually dry conditions prevailing in southeastern Tasmania during the sampling period.

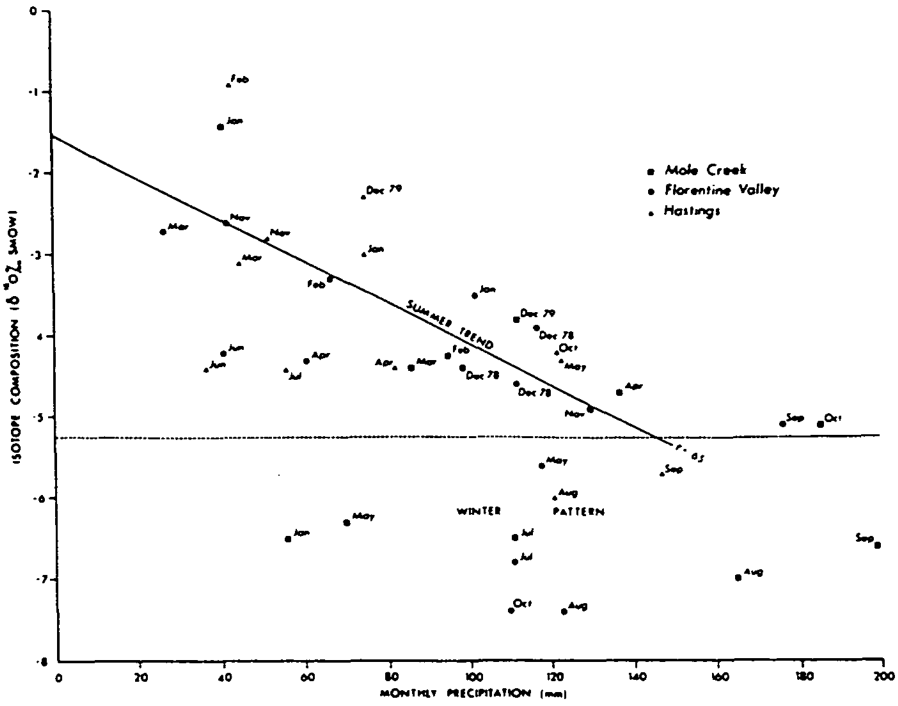

Figure 5. Graph of monthly precipitation against isotopic composition ($\delta^{18}O°/_{\circ\circ}$ SMOW) shows the amount effect during the summer months. (Name of month refers to month of collection of sample, e.g. sample labelled May covers period mid April-mid May). At Hastings and Florentine Valley amount effect can be observed for very dry months during winter.

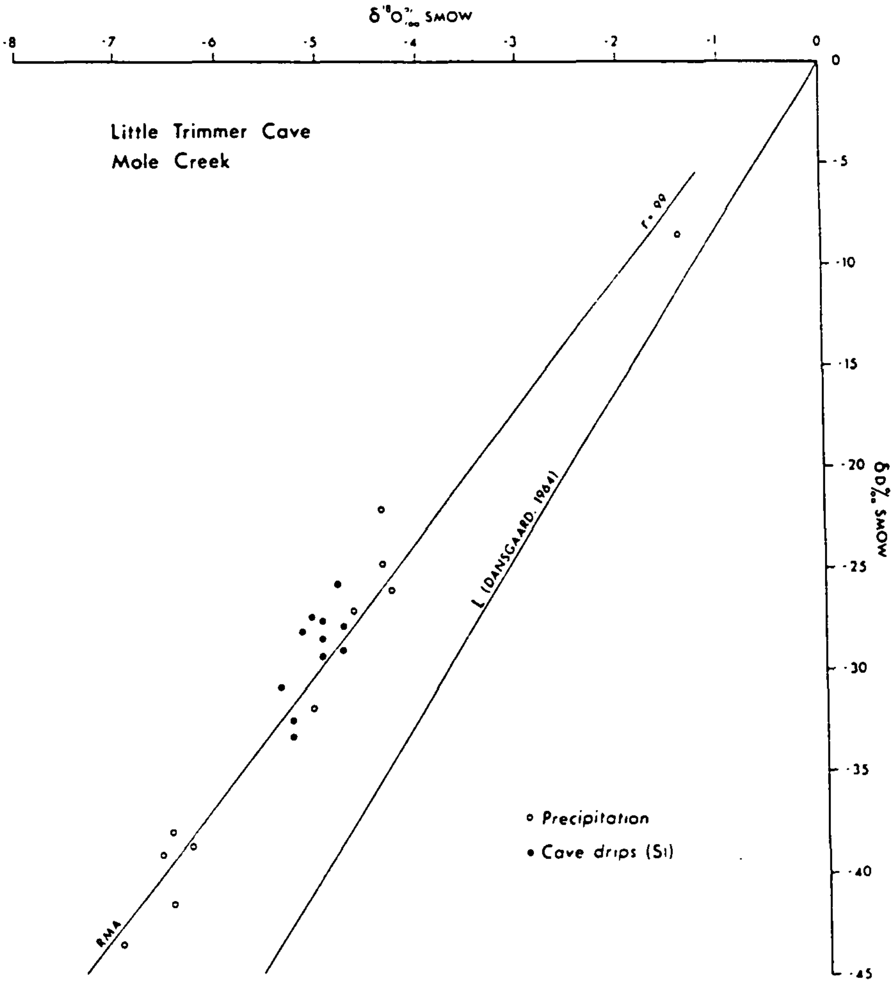

Figure 6. Relationships between monthly $\delta^{18}O$ and δD values for precipitation and cave drip (S_1) at Little Trimmer Cave, Mole Creek.

Cave temperatures

At each of the three cave sites the minimum and maximum temperatures were read monthly and the actual temperature at the time of the visit (instantaneous temperature) was also noted. Maximum temperature values for King George V Cave have been disregarded because the thermometer proved to be unreliable. The cave temperature ranges (°C) for 1979 are shown in Figure 8.

The mean annual temperatures calculated for the three caves from the instantaneous temperature measurements are:

Little Trimmer Cave	9.5°C
Frankcombe Cave	8.3°C
King George V Cave	9.4°C

These values should be compared with the mean annual temperatures calculated in Table I for the surface sites. At Mole Creek the agreement is close with the mean cave temperature 0.3°C higher than the calculated mean annual surface temperature. At Hastings a comparison shows the mean cave temperature to be 0.5°C lower than expected and in the Florentine Valley it is 0.9°C below the estimated mean annual surface temperature.

There is a marked contrast in the annual temperature range of the three cave sites. From north to south minimum temperature ranges are 0.9, 0.3 and 0.2°C while instantaneous temperature ranges are 1.2, 0.3 and 0.1°C. Maximum temperatures ranges are available only for Little Trimmer Cave 1.0°C and Frankcombe Cave 0.6°C. It is clear that Little Trimmer Cave has by far the greatest annual temperature range(approx. 1.0°C), the range at Frankcombe Cave is much smaller (approx. 0.4°C) while the cave site temperature variation for King George V Cave is extremely small (approx. 0.15°C). Only at Little Trimmer Cave is there a clearcut seasonal pattern. It is weakly developed in Frankcombe Cave and not at all in King George V Cave.

The reasons for the contrast between the three sites are not clear. All three have small entrances and are lacking in detectable air currents and all three sample sites are well removed from known entrances and from permanent underground streams. After the conclusion of the sampling programme the authors received information that Little Trimmer has a second entrance and this may explain the greater temperature variation at this site. It is also possible that other entrances, unknown to speleologists, exist closer to one or more of the sample sites but no evidence for this was found.

The long term temperature control on the cave atmosphere must be the surrounding bedrock (Lange, 1954, 2 refs). In the absence of significant air movement at the three sites, seasonal temperature variations by means of cave seepage waters entering through the roof of the caverns may be superimposed on the long term control. This would be most likely to have a significant effect where large amounts of seepage water move rapidly from the soil profile through the bedrock to the cave. If this is a factor it may go some way towards explaining the nearly constant temperature conditions in King George V Cave. This cave experienced very little seepage during 1979 compared with the other two. The site is also located in a permanently dry passage, while the other two sites are located in passages which may carry small flows of water after a prolonged period of heavy precipitation.

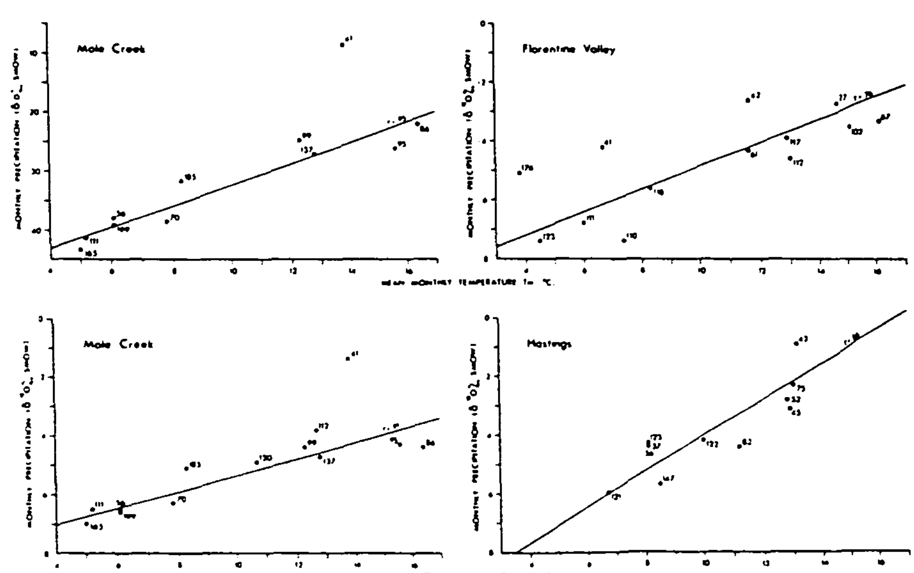

Figure 7. Statistical relationships between $\delta^{18}O$ (SMOW) values and mean monthly temperatures at the three stations as well as the relationship of δD SMOW values and mean monthly temperatures at Mole Creek.

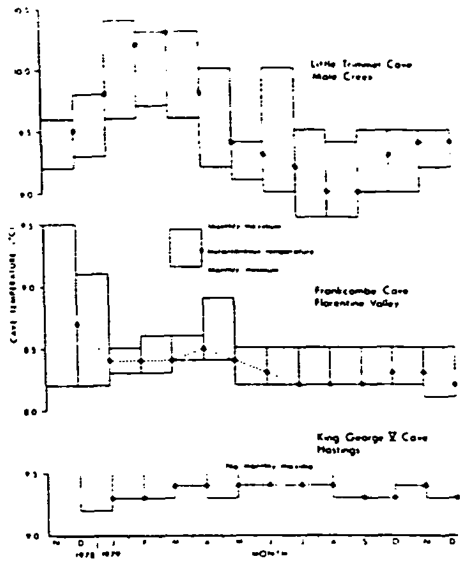

Figure 8. Monthly temperature observations at three cave sites.

Cave seepage rates

Since the water containers installed to collect seepage water overflowed during most months, at least in Little Trimmer and Frankcombe Caves, few absolute measurements of the amounts of drip water between monthly visits are available from these sites. Instantaneous drip rates were measured in Little Trimmer from August onwards and in Frankcombe Cave from July onwards. They are shown in Table II.

Like streamflows the drip rates show extreme variability with very high rates occurring during, and shortly after, periods of heavy rainfall and very low rates following prolonged drought conditions.

Isotopic composition of cave drips

Monthly samples of water were analysed from all six cave drip sites to determine the $^{18}O/^{16}O$ ratio. For the Hastings sites only a partial record was available because the drips dried up progressively during the year. In Little Trimmer Cave at drip site S1 the D/H ratio was determined for 11 out of 13 months of record. The patterns of variation are shown in Figure 9. The amount of isotopic variation in cave drip waters is reduced compared with that of precipitation (cf. Figures 2,3 and 4) presumably indicating the very considerable amount of storage and mixing of water in the soil.

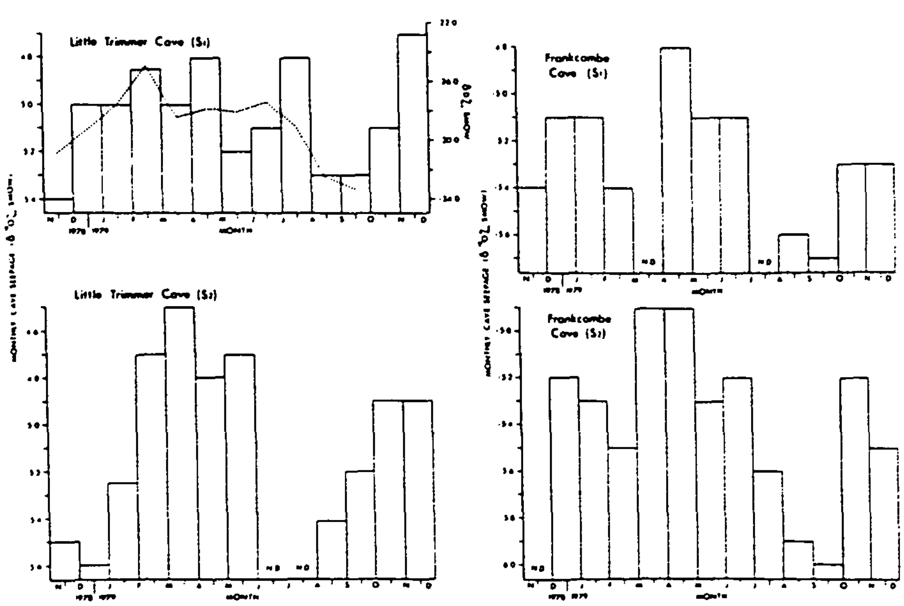

Figure 9. Monthly measurements of the isotopic composition of cave drip in Little Trimmer and Frankcombe Caves.

There is a marked contrast in the behavious of D/H and $^{18}O/^{16}O$ values. The former maintain the seasonality of pattern that characterises the precipitation at the surface site although there is clearly a lag effect of approximately two months for both the summer maximum and the winter minimum. The $^{18}O/^{16}O$ values still show a surprising range of variation with several isolated peaks of isotopically heavy values and with an almost complete removal of the seasonal cyclic pattern. The causes of non-seasonal variations in the $^{18}O/^{16}O$ values of drip waters are not known.

TABLE II. Instantaneous drip rates of cave seepage waters in litres/hour

Little Trimmer Cave			Frankcombe Cave		
Date	S1	S2	Date	S1	S2
-	-		24/7/79	.054	1.147
9/8/79	1.147	9.556	14/8/79	.420	3.211
11/9/79	.459	14.556	17/9/79	2.918	6.040
8/10/79	1.758	17.393	16/10/79	.510	3.058
9/11/79	.076	.917	15/11/79	.031	.287
11/12/79	.008	.612	10/12/79	3.823	5.734
Mean	.690	8.601	Mean	1.293	3.246

The weighted mean values of precipitation can only be compared with the arithmetic means of cave drip samples since average drip rates between monthly visits are not known.

In the case of Little Trimmer and Frankcombe Caves isotopic means of precipitation and cave drips are comparable but in the case of King George V Cave the cave drips are much lighter isotopically than would have been expected. The fact that the drips in King George V Cave dried up during the period of record suggests that the seepage water collected is not related to precipitation during 1979 but may well be derived from precipitation which fell during the previous winter. The fact that the cave drips failed to respond to the substantial spring rainfall from July to October (Figure 4) suggests a high capacity for water storage in the soil mantle and possibly low permeability of the Permian caprock above the cave. At drip site S1 in Little Trimmer the different behaviour of the $\delta^{18}O$ and δD content of water as it passes through the soil and overlying rock means that the close relationship found between the two sets of values for precipitation (Equation 2) is significantly lost in this movement. The equation for the relationship in cave drip waters is

$$\delta D = 10.78\,\delta^{18}O + 25.52 \quad (r = .70) \qquad (7)$$

The correlation just reaches significance at the 2°/o level. The application of t-tests indicates that neither the intercept term nor the slope value is significantly different from the corresponding values in Dansgaard's equation for the meteoric water-line.

TABLE III. Comparison of mean isotopic values (SMOW) between precipitation and cave drips.

Site		Precipitation (weighted mean)	Cave drips (arithmetic mean)
Little Trimmer Cave (Mole Creek)	S_1	-32.78 δD ‰	-29.13 δD ‰
	S_1	-5.40 $\delta^{18}O$ ‰	-5.04 $\delta^{18}O$ ‰
	S_2	-5.40 "	-5.04 "
Frankcombe Cave (Florentine Valley)	S_1	-5.27 "	-5.26 "
	S_2	-5.27 "	-5.38 "
King George V Cave (Hastings)	S_2	-4.76* "	-5.82 "

* Value adjusted for difference in altitude using a value of -0.40 ‰ $\delta^{18}O$/100 metres.

TABLE IV. Isotopic composition (PDB) of actively forming speleothems from three Tasmanian caves.

Sample No.	Cave	Nature of material	$\delta^{18}O$°/oo	$\delta^{13}C$°/oo
OX12	Little Trimmer	straw	-3.8	-8.0
OX15	"	"	-3.5	-9.7
OX19	"	flowstone	-3.8	-13.7
OX20	"	"	-3.5	-13.5
OX2	Frankcombe	Straw	-4.0	-8.4
OX3	"	"	-3.6	-6.2
OX7	"	"	-3.7	-5.7
OX1	King George V	Straw	-3.7	-12.0
OX5	"	"	-3.1	-10.1
OX8	"	"	-3.7	-10.4
OX9	"	"	-3.7	-8.7
OX10	"	"	-3.8	-7.9
OX11	"	"	-4.0	-10.3

TABLE V. Calculated temperatures of calcite deposition

Cave Site	Observed Mean Annual Temp. (°C)	Calculated Temperatures (°C) Minimum	Mean	Maximum
Little Trimmer	9.5	9.4	10.0	10.6
Frankcombe Cave	8.3	8.6	9.3	10.3
King George V (using seepage data)	9.4	4.6	6.8	8.1
King George V (using precipitation data)	9.4	9.3	11.2	12.6

Isotopic composition of speleothems

In order to determine whether present day deposition of calcite in the three caves is occurring under conditions of isotopic equilibrium, actively growing tips of straw stalactites were collected and analysed for their oxygen and carbon isotopic composition (Harmon, Schwarcz & Ford, 1978). In the case of Littler Trimmer Cave two samples of flowstone that had formed on plastic funnels used to collect cave drip water during 1979 were also analysed. A total of thirteen analyses was carried out and the results are shown in table IV.

Calculating average values for the three sites we obtain

	$\delta^{18}O$°/oo PDB	$\delta^{13}C$°/oo PDB
Little Trimmer Cave	-3.65	-11.23
Frankcombe Cave	-3.77	- 6.77
King George V Cave	-3.67	- 9.90

With the aid of these values and knowing the mean isotopic composition of cave drip water it is possible to calculate the temperature of deposition since the $^{18}O/^{16}O$ ratio of calcite formed in equilibrium with water decreases with increasing temperature. The equilibrium constant for the system calcite-water has been determined by O'Neil et al.(1969) and subsequently modified by O'Neil et al.(1975) as

$$10^3 \ln K_{c-w} = 2.78\ 10^6 T^{-2} - 2.89 \qquad (8)$$

where $K_{c-w} = (^{18}O/^{16}O)_c / (^{18}O/^{16}O)_w$ and T is the absolute temperature.

Using the mean isotopic composition of the seepage water at the three cave sites, temperatures of deposition were calculated for the mean, lowest and highest $^{18}O/^{16}O$ isotope ratio values of speleothems from each of those sites. Since it has already been suggested that the seepage water collected in King George V Cave during 1979 was not typical for this site the calculations were repeated using the weighted mean isotopic composition of precipitation adjusted for the difference in altitude between the cave and the surface station. The results of these calculations are shown in Table V.

Considering the small number of samples of calcite involved, the limitations of accuracy of measurement of $\delta^{18}O$ values and the fact that arithmetic means of the isotopic composition of seepage had to be used the agreement with observed temperatures is considered quite satisfactory.

The King George V Cave seepage waters do not appear to be representative of normal conditions. As has been suggested earlier they appear to be abnormally light isotopically. Ignoring these results in Table V the calculated temperatures are slightly higher at all three sites than the observed values. This may well reflect slight differences in calibration of $\delta^{18}O$ values between laboratories.

It is confirmed that speleothems currently forming at the three sites investigated are depositing calcite under conditions of isotopic equilibrium.

The $^{12}C/^{13}C$ isotope ratios are highly variable but values for Frankcombe Cave are significantly heavier isotopically than for the other two sites. This may be due to recent clearfelling and burning in the area.

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Ritchie Wooley and Denis Charlesworth assisted with the stable isotope analyses and the figures were drawn by Kate Morris and Guus van de Geer. The manuscript was typed by Terese Hughes.

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Radiometric dating of Tasmanian speleothems—evidence of cave evolution and climatic change

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ABSTRACT

$^{230}Th/^{234}U$ dates on Tasmanian speleothems enable preliminary estimates to be made of ages and rates of evolution of Tasmanian karst caves. Occurrence of speleothem deposition has varied markedly in time, the highest abundance being associated with marine isotope stages 1 and 5. Rates of growth of from 21 to 79 mm/ka have been determined for four equilibrium diameter stalagmites, some of which are known or expected to provide suitable material for isotopic analysis.

KEY WORDS: radiometric dating, speleothems, cave evolution, weathering rinds, stalagmite growth rates, climatic change.

INTRODUCTION

Karst in Tasmania has developed predominantly in Ordovician Gordon Limestone, which is a peritidal sediment with a tropical fossil assemblage dominated by algae and corals. A smaller number of caves are found in dolomites of presumed late Precambrian age. The term 'speleothem' is applied to mineral deposits in caves precipitated from aqueous solutions that are usually derived from seepage waters, which enter from above. On the basis of their mode of deposition and morphology, such deposits may be classified as stalactites, stalagmites, flowstones and rimstones, as well as a number of less common varieties. In Tasmanian caves they consist predominantly of calcium carbonates deposited as calcite.

The advent of uranium-series dating of speleothems has opened up new prospects for the study of geomorphological and climatological changes during the Pleistocene, particularly where surficial sediments are either lacking or cannot be dated by existing methods. Surface deposits are commonly altered by weathering and pedogenic processes and offer poor chances of preservation of biological material. Karst caves frequently provide suitable sites for the accumulation of chemical, detrital and organic deposits. In cave environments climatic variation is much reduced, and the chances of long-term preservation of both sediments and fossils are greatly enhanced.

The $^{230}Th/^{234}U$ uranium-series disequilibrium method of dating speleothems has proved to be reliable, provided that samples meet certain basic criteria. These, together with the analytical methods used, have been detailed by Harmon et al. (1975) and Gascoyne et al. (1978). The technique is also widely used for the dating of corals and certain molluscs, and has been applied, with varying degrees of success, to the dating of bone (Bischoff & Rosenbauer, 1981), lake salt (Peng et al., 1978), travertine (Harmon et al., 1980), desert varnish (Knauss & Ku, 1980), and pedogenic carbonates (Ku et al., 1979).

The technique assumes that uranium is co-precipitated with calcium carbonate from waters that are free of thorium. Samples should have uranium concentrations of at least 0.1%. They are rejected if (1) they contain either visible impurities or in excess of 1% detrital material upon dissolution, and (2) they have $^{230}Th/^{232}Th$ ratios of < 16, except for samples of age < 10 ka BP. ^{234}U decays to ^{230}Th, so that the ratio $^{230}Th/^{234}U$ gives an estimate of age until equilibrium conditions are obtained, because ^{230}Th is itself subject to radioactive decay. The age of a speleothem sample is given by the equation:

$$\left[\frac{^{230}Th}{^{234}U}\right] = \frac{1-e^{-\lambda_{230}t}}{[^{234}U/^{238}U]} + \left(\frac{\lambda_{230}}{\lambda_{230}-\lambda_{234}}\right)\left(1 - \frac{1}{[^{234}U/^{238}U]}\right)\left(1-e^{-(\lambda_{230}-\lambda_{234})t}\right)$$

where $[^{230}Th/^{234}U]$ and $[^{234}U/^{238}U]$ are the measured isotope activity ratios, λ_{230} and λ_{234} the decay constants of ^{230}Th and ^{234}U, respectively ($\lambda_{230} = 9.217 \times 10^{-6}$ y^{-1} and $\lambda_{234} = 2.806 \times 10^{-6}$ y^{-1}), and t is the time elapsed since deposition of the sample. The method has a range of 1000 to 400 000 years BP, but becomes very imprecise near the limits of this range. The ratio $^{234}U/^{238}U$ is required to

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adjust the age estimates obtained from the $^{230}Th/^{234}U$ ratio. The effects of variations in the ratio become progressively more marked as the age of the sample increases.

If thorium-bearing detrital minerals are present in the sample, the measured age will be too high because of the addition of non-radiogenic ^{230}Th. This detrital ^{230}Th is always accompanied by ^{232}Th. Hence the ratio $^{230}Th/^{232}Th$ is measured. Where the ratio is small the precision of the date is reduced, but a rough correction can be made to improve the age estimate according to the modified age equation:

$$[^{230}Th/^{234}U] - [^{232}Th/^{234}U]B_o e^{(-\lambda_{230} t)} = \frac{1-e^{-\lambda_{230} t}}{[^{234}U/^{238}U]} + \left(\frac{\lambda_{230}}{\lambda_{230}-\lambda_{234}}\right)\left(1 - \frac{1}{[^{234}U/^{238}U]}\right)\left(1-e^{-(\lambda_{230}-\lambda_{234})t}\right),$$

where B_o is the initial $^{230}Th/^{232}Th$ ratio at the time of deposition, which must be independently determined (Schwarcz, 1980).

The technique can be applied to four aspects of Tasmanian caves that are of importance in increasing our understanding of past changes in climate and the nature and magnitude of geomorphic processes, namely:

(1) The chronology and age of cave development (Hess & Harmon, 1981; Atkinson et al., 1978).
(2) The frequency distribution of ages of speleothems, which has been shown elsewhere to be

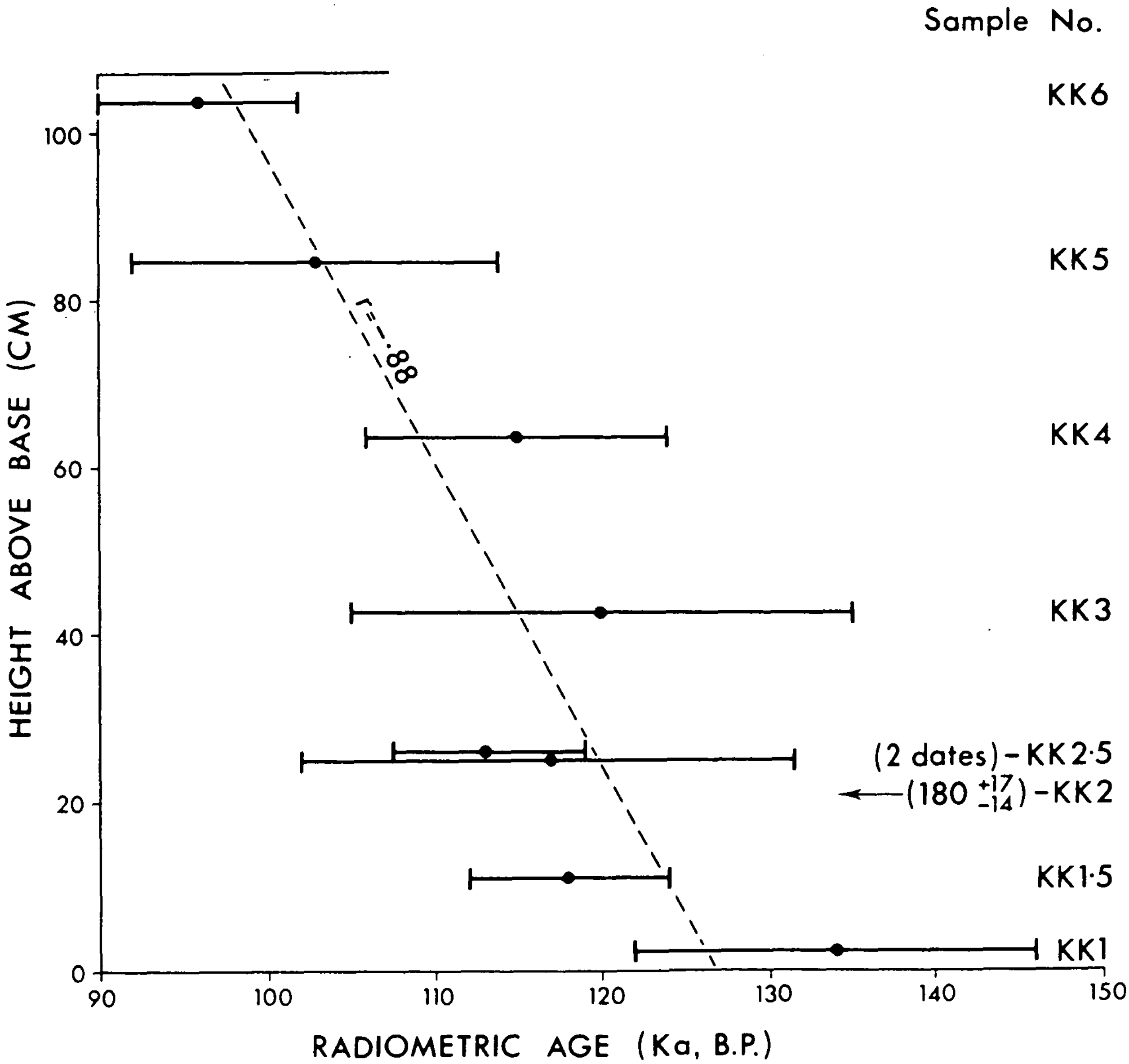

Fig. 1. Regression of distance above base on radiometric age for Kubla Khan Stalagmite (KK) from a cave at Mole Creek.

Table 1. Uranium concentrations, isotope ratios and calculated ages of Tasmanian speleothems.

Sample	Location	Area	U (ppm)	$^{230}Th/^{234}U$	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	Calculated age (Ka BP)	Code
UT7a	Frankcombe Cave	2	.05	.13 ± .08	1.46 ± .35	> 1000	15 ± 10	gb
UT7b	" "	2	.06	.061 ± .15	.84 ± .18	> 1000	7 ± 17	gm
UT7c	" "	2	.05	> .001	1.24 ± .96	-	modern	gt
UT9	Exit Cave	4	.15	.048 ± .03	3.17 ± .17	> 1000	5 ± 3	ft
UT10a	" "	4	.18	1.036 ± .08	1.43 ± .09	16	315 $^{+\infty}_{-70}$	gb
UT10b	" "	4	.14	1.060 ± .30	1.05 ± .11	66	> 400	gm
UT10c	" "	4	.12	1.015 ± .10	1.88 ± .15	28	249 ± 70	gt
UT11	" "	4	.10	.901 ± .10	2.03 ± .27	100	181 ± 60	gb
UT5	Pleisto Scene Cave	6	.15	< .001	1.08 ± .06	-	modern	c
UT22	Tinys Watch Hole	5	.10	.04 ± .03	2.34 ± .05	40	5 ± 3	gb
UT21	Ghengis Khan	1	.20	.88 ± .02	2.04 ± .01	28	172 ± 9	gb
UT20	" "	1	.08	.23 ± .04	2.69 ± .05	> 1000	25 ± 4	g
UT17	Exit Cave	4	2.44	.66 ± .01	1.13 ± .01	54	112 ± 3	gt
UT16	" "	4	?	.22 ± .02	2.58 ± .03	1000	26 ± 3	gb
LT7	Little Trimmer	1	.91	.68 ± .02	2.28 ± .02	62	110 ± 6	g
LT8	" "	1	.94	.66 ± .03	2.19 ± .01	200	102 ± 8	g
LT2	" "	1	1.1	.66 ± .02	2.37 ± .01	44	102 ± 5	g
LT3	" "	1	.8	.62 ± .02	2.35 ± .02	145	93 ± 4	g
LT4	" "	1	.8	.59 ± .02	2.35 ± .01	234	88 ± 4	g
LT5	" "	1	.6	.57 ± .02	2.02 ± .01	100	82 ± 4	g
LT6	" "	1	.7	.54 ± .03	2.51 ± .02	229	78 ± 6	gt
KK1	Kubla Khan Cave	1	.12	.74 ± .04	1.44 ± .03	28	134 ± 12	gb
KK1.5	" " "	1	.21	.70 ± .02	1.85 ± .06	126	118 ± 6	g
KK2	" " "	1	.19	.88 ± .03	1.68 ± .02	43	180 $^{+17}_{-14}$	g
KK2.5	" " "	1	(.21	.68 ± .02	1.97 ± .05	96	113 ± 6	g
		1	(.27	.70 ± .05	1.90 ± .02	190	117 ± 15	g
KK3	" " "	1	.24	.72 ± .05	1.84 ± .02	51	120 ± 15	g
KK4	" " "	1	.14	.68 ± .03	1.60 ± .02	38	115 ± 9	g
KK5	" " "	1	.14	.65 ± .04	1.84 ± .04	48	103 ± 11	g
KK6	" " "	1	.13	.62 ± .03	1.78 ± .03	> 200	96 ± 6	gt
UT29	Matchlight Cavern	3	12.7	.56 ± .03	3.69 ± .03	148	80 ± 6	gb
UT31	" "	3	.18	.95 ± .02	3.66 ± .01	49	189 $^{+6}_{-12}$	gt
UT32	" "	3	4.9	.99 ± .03	2.76 ± .02	135	231 $^{+24}_{-20}$	gb
LX-Z	Little Trimmer	1	1.5	.58 ± .02	1.57 ± .02	80	89 ± 5	gb
LX-Y	" "	1	.86	.56 ± .02	2.31 ± .02	83	82 ± 5	gm
LX-X	" "	1	.80	.53 ± .02	2.35 ± .03	200	75 ± 5	gt
LC1	Lynds Cave	1	.26	.15 ± .01	2.38 ± .03	115	17 ± 2	gb
LC2	" "	1	.25	.10 ± .01	2.91 ± .03	63	11 ± 1	g
LC3	" "	1	.33	.07 ± .01	2.98 ± .03	> 200	7 ± 1	g
LC4	" "	1	.28	.02	2.43 ± .03	> 200	modern	g
UT12*	Pleisto Scene Cave	6	1.7	.17 ± .03	.93 ± .04	> 1000	20 ± 4	c
UT75*	Iron Monarch	7	10.4	.01 ± .003	1.68 ± .005	56	2	gb
UT77*	Blister Cave	7	37.8	.15 ± .03	1.64 ± .01	782	17 ± 3	gb
UT78*	" "	7	8.0	.17 ± .04	1.46 ± .01	399	19 ± 4	gb

First column: * previously published date. Second column: number indicates area as shown in Figure 1. Last column: c - stalactite, g - stalagmite, f - flowstone, b, m and t indicate basal, middle and top layers.

related to climatic conditions at the surface (Harmon et al., 1977; Atkinson et al., 1978).

(3) The stratigraphic relationships of dateable speleothems with clastic deposits, some containing bone and archaeological material (Goede et al., 1978). The clastic deposits may themselves contain information about past climates and geomorphic processes. The development of weathering rinds on some igneous clasts provides a potential method for time correlation of deposits from cave to cave. Rind thickness appears to be predominantly a function of time in the relatively unchanging subterranean environment. $^{230}Th/^{234}U$ dating opens up the possibility of assigning maximum and minimum ages to some of these deposits.

(4) The dating of uniform-diameter stalagmites. The term is used to describe stalagmites that do not show a progressive thickening towards the base. They are frequently found to have grown at approximately constant rates, and may be suitable for analyses of $^{18}O/^{16}O$, $^{13}C/^{12}C$ and D/H isotopic ratios, which can be used as climatic and biological indicators of the surface environment during the period of accumulation (Harmon et al., 1978*a,b*).

Where growth has occurred at a constant rate and multiple $^{230}Th/^{234}U$ dates are available, a time scale can be determined by regression analysis of distance-above-base against radiometric age (Fig. 1). This procedure reduces the random error involved in individual age determinations and also tests the reliability of the dating method. It provides excellent time control and a reliable estimate of the long-term rate of speleothem growth is obtained. This is particularly valuable where axial profiles of isotopic ratios are subsequently constructed.

The radiometric ages, uranium concentrations and isotope ratios of 43 Tasmanian speleothems are shown in Table 1. Asymmetric age errors are shown for some older samples. Such errors are significant only with ages > 150 ka BP. Four of the dates have been previously published: UT75, 77 and 78 in Goede, Harmon & Kiernan (1979) and UT12 in Goede, Murray & Harmon (1978). The first three samples were collected from raised seacaves developed in sheared quartzites on the SW coast of King Island, and the fourth was collected from a small karst cave in Precambrian dolomite in north-western Tasmania. UT5 was also collected from the second locality. The other 38 samples have been collected from caves developed in Ordovician limestones. The localities are shown in Figure 2.

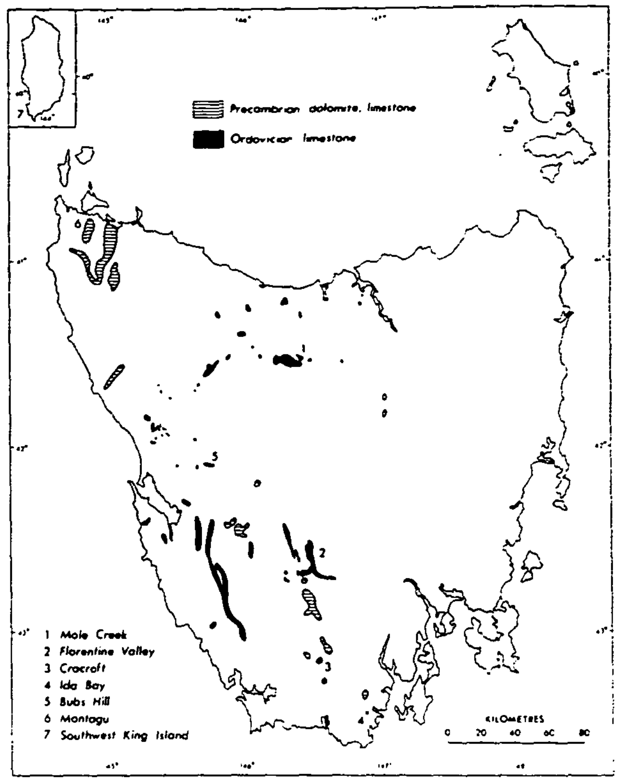

Fig. 2. Location map of karst areas in Tasmania.

DURATION OF CAVE DEVELOPMENT

Ages prior to the beginning of the Last Interglacial (> 130 ka BP) have so far been obtained from three Tasmanian caves. Exit Cave in southern Tasmania is Australia's most extensive cave system, with some 16 km of known passageways. The cave is developed in gently dipping Ordivician limestone. The oldest four dates (UT10a, b and c and UT11) were obtained from an upper level of the cave, where low-roofed passages are underlain by gravelly alluvium. The three UT10 dates are all taken from a single short stalagmite, which shows three distinct phases of deposition. As the two oldest are at or beyond the range of $^{230}Th/^{234}U$ dating, the underlying alluvium is older than 400 000 years. Roof exposures of rock pendants are separated by anastomosing half-tubes, and indicate that the passages developed by downcutting from a network of phreatic tubes developed parallel or subparallel to the bedding. Cave development had already reached the vadose stage prior to accumulation of the alluvium.

Undissected alluvial floors lie some 25 m above the present-day level of the underground stream. If a minimum possible age of 400 000 years BP is assumed for the alluvial sediments, a maximum rate of downcutting of 63 mm/ka is indicated. Since the long-term rate of downcutting is considered by us to be in harmony with the general lowering of the surrounding major valleys, this also provides an estimate of the maximum rate of valley lowering over the last 400 000 years. If, during the Quaternary, relief in the area evolved in an equilibrium manner (Hack, 1960) with rates of valley lowering and hillcrest reduction approximately equal, then the rate of downcutting would also provide an estimate of surface lowering of the landscape (Ford et al., 1981).

The rate is in fact comparable with rates of surface lowering of limestone quoted by Jennings (1971) and surface lowering of normal relief suggested by Young (1969).

Matchlight Cavern is located in the Cracroft River Valley in southern Tasmania. It is developed in Ordovician limestone, which dips south-easterly at 25°–36°. Major passages show alignment along the strike (Goede, 1977). The flat floors of the cavern represent the depositional surface of ancient alluvial sediments. These have subsequently been dissected by water erosion in some places, but are covered by wall and ceiling breakdown in others. The cavern presently contains no running water, but directly overlies the main passage of Judds Cavern, which contains a large active stream. Although there is no known penetrable connection between the two cave systems, Matchlight Cavern clearly represents a remnant of an early phase of stream activity.

The difference in height between the depositional surface of the alluvium in Matchlight Cavern and the stream level in Judds Cavern immediately below has not been accurately surveyed, but lies between 20 and 40 m. Samples UT29, 31 and 32 provide ages for three stalagmites that developed either on the alluvial sediments or on overlying rock breakdown in Matchlight Cavern. The oldest date of $189 {}^{+6}_{-12}$ ka BP for the basal layers of a 20 cm high stalagmite permits calculation of a maximum rate of downcutting of the Judds Cavern stream of between 106 and 212 mm/ka.

Ghengis Khan Cave is developed in strongly folded Ordovician limestone in the Mole Creek area of northern Tasmania. It is a high-level relic system no longer subject to modification by running water. The cave lies close to Kubla Khan—an extensive multi-level cave system with a long history of development, which contains an active underground stream in its lowest level. The exact relationship between the two caves has not been investigated, but their evolution is likely to have been closely linked. The dated material has been collected from the main chamber in Ghengis Khan, which lies at least 50 m above the Kubla Khan stream. An age estimate of 172 ± 9 ka BP was obtained from the base of a broken stalagmite (UT21) developed upon roof-fall, but the cave may well be much older.

These dates indicate that some Tasmanian caves have a long history which, at least in the case of Exit Cave, goes back well beyond the limits of $^{230}Th/^{234}U$ dating.

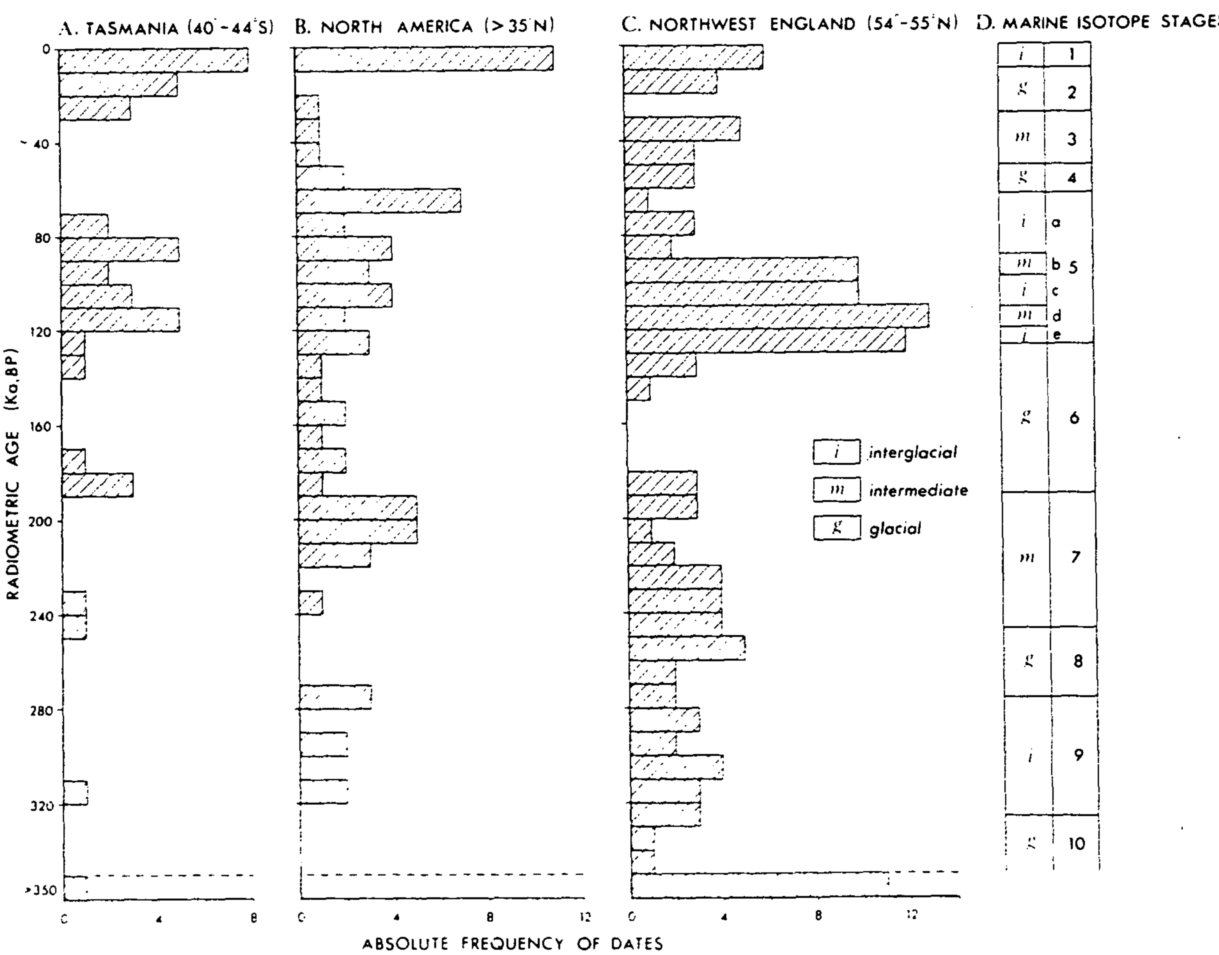

Fig. 3. Growth-frequency distribution of speleothems in Tasmania (A), North America (B) and NW England (C) and the corresponding sequence of marine isotope stages (D).

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GROWTH-FREQUENCY DISTRIBUTION

The frequency distribution of the 43 $^{230}Th/^{234}U$ age determinations for Tasmanian speleothems has been plotted against time as a histogram with intervals of 10 ka (Fig. 3A). For comparison, two other histograms are shown for temperate regions in the Northern Hemisphere (Harmon et al., 1975; Gascoyne, 1981). Figure 3B represents the frequency distribution of 70 North American dates (> 35°N) and Figure 3C is a similar diagram for 134 dates obtained from caves in the Yorkshire Dales in NW England (54°–55°N). Since the Tasmanian sample is rather small, no meaning can be attached to the pattern beyond 200 ka BP. These are compared with marine isotope stages 1 to 10 in Figure 3D. The time scale used is the 'TUNE-UP' scale of Hays et al. (1976).

All three histograms show basically similar patterns, with either a low frequency or absence of dates during cold periods (isotope stages 2, 4 and 6) and a high frequency during warmer intervals (isotope stages 1, 3, 5 and 7). There are some minor but curious differences. So far the Tasmanian sample shows a complete absence of dates between 75 and 26 ka BP, but no less than eight dates between 30 and 10 ka BP—a period generally regarded as one of maximum cold and maximum extent of glacial ice (Colhoun, 1975, 1978). Pollen evidence also suggests that most of this period was relatively dry (Colhoun et al., 1982) although there are obvious difficulties in separating temperature and precipitation effects.

Out of the eight dates between 30 and 10 ka BP, six are basal dates on stalagmites, which indicate the time of initiation of carbonate deposition. Four of the dates cluster around 15 to 19 ka BP (UT7a, LC7, UT77 and UT78), and the remaining two centre on 25 to 26 ka BP (UT16 and UT20). The first group may indicate rapid amelioration after the glacial maximum at about 18 ka BP. Multiple dates from the LC stalagmite (Lynds Cave, Mole Creek) indicate continuous carbonate deposition from 17 ± 2 ka BP—well into the Holocene.

AGE RELATIONSHIPS WITH CLASTIC SEDIMENTS

Basal dates obtained from stalagmites and flowstones deposited on top of clastic sediments provide minimum ages for such deposits. Detrital speleothem fragments suitable for dating within the sediments permit calculation of a maximum date for the initiation of clastic deposition. However, even if both a minimum and a maximum date can be obtained, there may still be wide limits within which the age of a clastic deposit can vary. A detrital speleothem fragment may be very much older than the sediment in which it is incorporated, whereas a stalagmite or flowstone layer overlying a clastic deposit may be very much younger. Particularly in the second case, considerations of cave conservation restrict sampling. Hence collection may be limited to material that has already been broken.

As we have already shown, an alluvial fill in an upper-level passage of Exit Cave has a minimum age > 400 ka BP, since the basal and middle layers of at least one stalagmite (UT10) growing on the sediments appear to be beyond the range of Th/U dating.

In a different part of this cave system, a large complex debris cone occurs in a passage drained by a small tributary stream. This cone appears to originate from a vertical shaft that rises towards the surface from a system of basically horizontal passages. Such shafts are widespread in Exit Cave, and are commonly located at or close to the boundary between the limestone and the overlying Permian caprock (Goede, 1969). The Permian sequence consists of basal tillites overlain by fossiliferous shallow marine siltstones and fine-grained sandstones. The cone contains numerous angular fragments of caprock sediments, which are relatively unweathered and are set in a poorly sorted, sandy matrix. The sediments are interpreted as the product of mechanical weathering when vegetation was poorly developed or absent at the surface (300 m above present-day sealevel). As this would require a lowering of the tree-line of at least 700 m, cold-climate conditions are indicated. The small underground stream has dissected the toe of the cone to a depth of at least 4 m since deposition ceased.

From the upper part of a 7 cm-high stalagmite in situ on an undissected part of the cone surface, and age of 112 ± 3 ka BP was obtained, indicating a Last Interglacial age. The basal portion was not dateable because of detrital contamination. The accumulation of the debris cone occurred either during the Penultimate Glacial Stage (isotope stage 6) or an earlier cold phase. As no detrital speleothems have so far been found in the deposits, a maximum age cannot be established.

A detrital stalactite (UT12) was used by Goede et al. (1978) to establish a maximum age for two superimposed breccias in a small dolomite cave (Pleisto Scene Cave) near Montagu in NW Tasmania. The age of the breccias is of particular interest, since they have yielded elements of a late Pleistocene megafauna (Murray & Goede, 1977). The stalactite, which apparently broke off the roof during accumulation of the lower breccia, provides a maximum age of 20 ± 4 ka BP for the deposits. Attempts to date basal flowstone that overlies the younger breccia by means of $^{230}Th/^{234}U$ dating were unsuccessful, because of detrital contamination. The flowstone was subsequently assayed by ^{14}C at 17.67 ± .18 ka BP (Pta-250b) but this assay has not been corrected for ^{13}C (Fig. 4). Where such corrections have been made, true C14 ages are found to be between 1 and 5 ka younger (Hendy, 1970). Breccia accumulation therefore had definitely ceased by 12.5 ka BP. A combination of $^{230}Th/^{234}U$ and ^{14}C dating of speleothems has shown that the age of the two breccias is likely to lie between 20 and 12.5 ka BP. This is consistent with the earlier conclusion reached by Goede, based on the physical nature of the older breccia, that it accumulated

Fig. 4. Late Pleistocene bone breccia overlain by flowstone in Pleisto Scene Cave, Montagu, northwestern Tasmania. A ^{14}C assay of basal flowstone shown in this figure is reported in the text.

under conditions approaching maximum cold during the Last Glaciation (Murray & Goede, 1977).

$^{230}Th/^{234}U$ dating has so far not been entirely successful in providing close age limits for all clastic sediments. A vast majority of Tasmanian karst caves, which nearly always contain active streams at the lowest level, show a relatively late phase of alluvial aggradation. For the most part, the evidence for this consists of exogenic gravels, with pebbles up to 15 cm or more in diameter, set in a matrix of poorly sorted clayey and silty sands. The deposits are commonly many metres in thickness. Burns (1960) described a 7 m-thick example of this type in Talus Chamber, Marakoopa Cave (Mole Creek). Goede & Murray (1977) recorded a similar deposit from Beginners Luck Cave (Florentine Valley) with a maximum depth of at least 5 m. Limestone fragments are rare in the gravels and the rock-types are usually sedimentary, igneous and metamorphic clasts brought into the caves by streams from more elevated areas of non-carbonate rocks which border the karst areas (Fig. 5).

Such deposits commonly include dolerite clasts, which show rather uniform weathering rinds and appear to provide a means for correlation of deposits from cave to cave. The measurement technique consists of collecting 30 dolerite clasts, breaking each with a hammer, and measuring the rind thickness at four points around the perimeter (away from corners) to obtain an average value for each pebble. The mean and standard deviation of the average values are then calculated, after disregarding occasional pebbles, the thicknesses of which were far removed from the distribution of rind thicknesses for the rest of the sample (Colman & Pierce, 1981). Rind-thickness measurements from several sites yield mean values between 0.71 and 1.06 mm (Fig. 6). At this stage the evidence suggests that, in Tasmanian caves examined so far, alluvial deposits that contain dolerite clasts with this characteristic range of thicknesses can be regarded as belonging to the Beginners Luck alluvial phase.

One exception so far to the close to 1 mm average rind thickness values is an alluvial fill in Spider Cave (Mole Creek) where dolerite pebbles with extremely thin ($\leq$ 0.2 mm) weathering rinds were found. The cave lies adjacent to a glaciofluvial outwash fan, from which the gravels appear to have been derived, and which shows similar minimal weathering rinds. Such minimal rind thicknesses are widely associated in Tasmania with glacial deposits laid down during the Last Glacial Maximum, which is generally believed to have occurred at approximately 18 ka BP.

Basal $^{230}Th/^{234}U$ dates for stalagmites growing on Beginners Luck alluvium have been obtained from three sites, and have yielded ages of 5 $\pm$ 3 ka BP (UT9), 17 $\pm$ 2 ka BP (LC1) and 5 $\pm$ 3 ka BP (UT22) (Table 1). At Beginners Luck Cave the

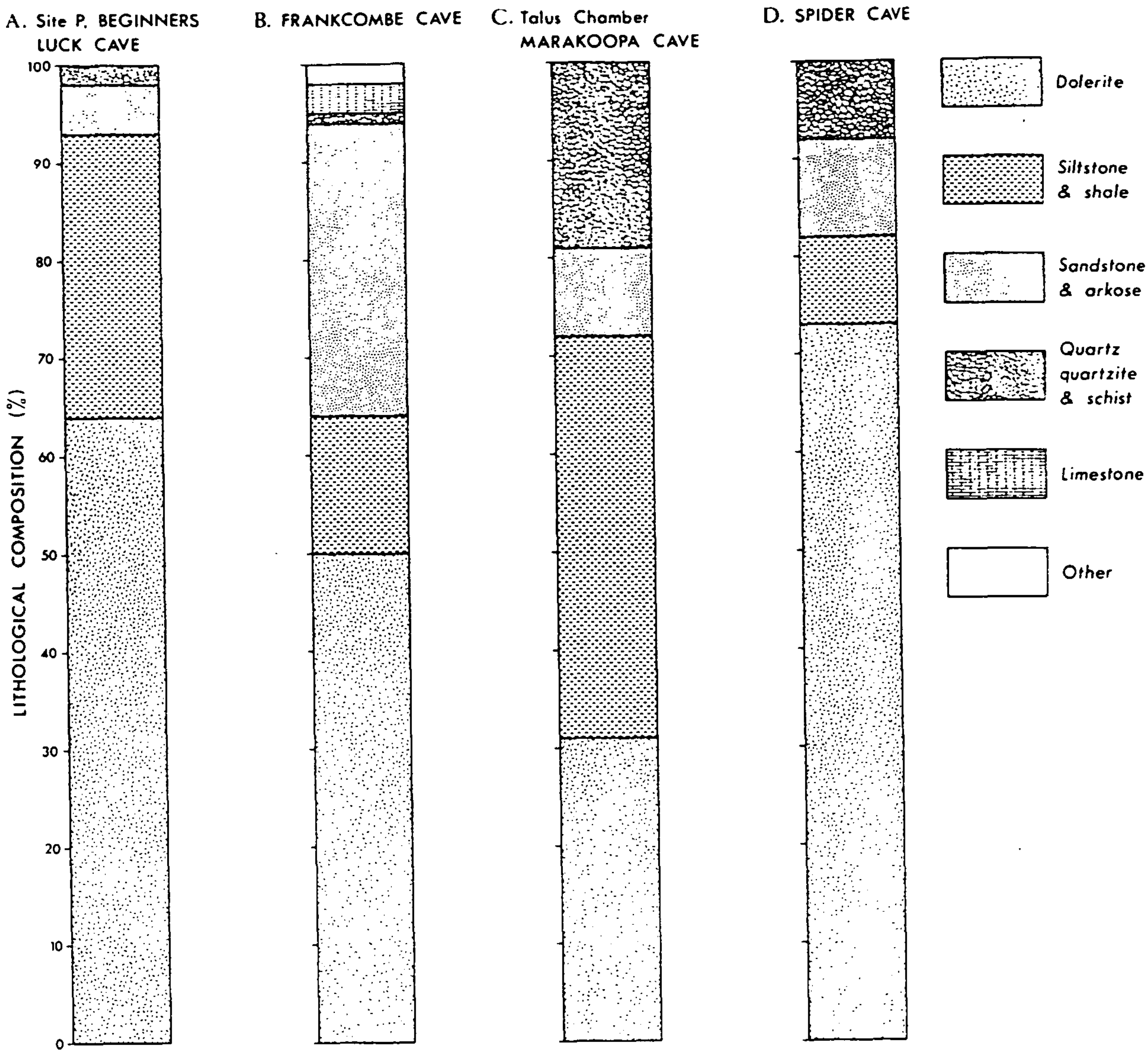

Fig. 5. Lithological composition of alluvial gravels from two cave sites in the Florentine Valley and two from the Mole Creek area.

alluvium is overlain by a limestone breccia which on the basis of ^{14}C dating of charcoal and aspartic acid dating of bone (Murray et al., 1980) has been assigned an age of 20 ka BP. The alluvium is clearly older than 20 ka BP by some amount.

The evidence for a maximum age is more circumstantial. At site P, Beginners Luck Cave, where the alluvium is overlain by the dated breccia with only slight erosional disconformity (Goede & Murray, 1977), there is no evidence for a phase of speleothem deposition between the two. There has been abundant speleothem deposition at the same site since the breccia was deposited. The growth-frequency distribution of Tasmanian speleothems shows a period of abundant speleothem deposition during the Last Interglacial (130–75 ka BP), whereas none occurred in the time between the deposition of the alluvium and the breccia. This points towards a maximum age of 75 ka BP for the Beginners Luck alluvial phase.

The minimum age estimate of 20 ka BP can be improved by comparing weathering rind thicknesses on dolerite pebbles in the alluvium with those in alluvial deposits generally believed to have been deposited during the Last Glacial Maximum (18 ka BP). The latter are usually characterised by minimal weathering rinds ($\leqslant$ 0.2 mm). At Mole Creek, such rinds are found in Spider Cave and in the adjacent glaciofluvial outwash fan, whereas in the Florentine Valley, outwash gravels with similar weathering characteristics are found only 2 km to the south of the Beginners Luck site.

In the Mole Creek area, alluvium dating from the Beginners Luck phase has been identified on the basis of weathering rind measurements from Talus Chamber, Marakoopa Cave (Fig. 4, DR8) and, from observation only, is also known to occur in a number of other caves in the area. In the Florentine Valley measurements have been made on samples from

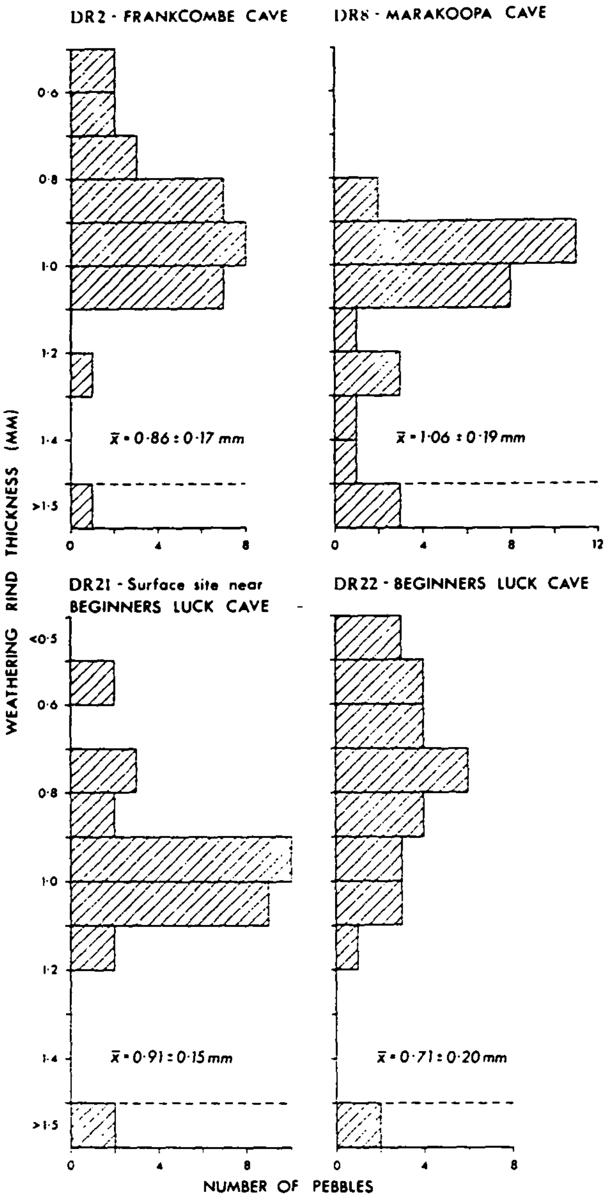

Fig. 6. Weathering-rind thickness distributions on dolerite pebbles from three cave samples and one surface sample deposited during the Beginners Luck alluvial phase.

Frankcombe and Beginners Luck Caves (Fig. 6, DR2 and DR22). Once again alluvial deposits with similar weathering characteristics are known from a number of other caves in the Florentine Valley. At the Beginners Luck site the alluvium can be traced almost continuously from inside the cave to the alluvial surface that partly surrounds the hill in which the cave developed. A sample of the surface alluvium (Fig. 6, DR21) was collected from a bulldozer scrape at a depth of 1.5–1.8 m—well below the zone of organic enrichment where accelerated weathering might have occurred.

The Beginners Luck Cave alluvial sediments at the type locality and the surface alluvial deposits with which they can be correlated thus show weathering rinds that are approximately four times as thick as those of dolerite pebbles found in both underground and surface alluvium associated with glaciofluvial deposition during the Last Glacial Maximum.

Tasmanian rinds on dolerite pebbles buried in a matrix appear to have developed in a very similar manner to weathering rinds on andesitic and basaltic stones in tills and glaciofluvial deposits examined by Colman & Pierce (1981) in the western United States. These authors found that 7000 years may be necessary before the weathering rind is initiated. If a similar estimate applies to the Tasmanian situation, the minimal weathering rinds ($\leqslant$ 0.2 mm) found on dolerite pebbles represent approximately 11 000 years of rind formation. Colman & Pierce (1981) and Colman (1981) have also shown that the rate of weathering-rind formation tends to decrease with time and that the assumption of a constant weathering rate will give a minimum age estimate.

The minimum age of the Beginners Luck alluvium can be estimated if we assume an age of 18 ka BP for fluvioglacial deposits associated with the Last Glacial Maximum, a constant weathering rate, and a lag period of 7000 years for the initiation of rind development. The minimum age calculated in this way is approximately 50 ka BP. We conclude that the age of the Beginners Luck alluvium is likely to lie between 50 and 75 ka BP.

The fact that, with rare exceptions, the dolerite pebbles are weathered uniformly suggests a lack of pre-depositional weathering. This, combined with the faceted nature of many pebbles and the low degree of rounding (Goede & Murray, 1977), suggests derivation by frost weathering and transport by short, high-energy streams under cold and wet climatic conditions. Deposition most probably occurred during isotope stage 4 at 61–73 ka BP (Hays et al., 1976). The age of this depositional event is important because it brought about widespread diversion of underground drainage and, at least in some cases, a temporary return to surface drainage.

The foregoing does not imply that pebbles in caves necessarily experience the same rate of rind development as those in surface deposits. Over longer periods of time climatic and biological factors can be expected to favour more rapid rind development at surface sites, particularly at shallow depths where chelation processes can be expected to play an increasingly important role. In contrast, weathering of cave pebbles may be retarded as alluvial exposures are sealed in by subsequent speleothem deposition.

GROWTH RATES OF UNIFORM-DIAMETER STALAGMITES

Uniform-diameter stalagmites, such as the one shown in Figure 7, are frequently found to have grown at constant rates (Harmon et al., 1975). They are of particular interest because studies of isotopic ratios of $^{18}O/^{16}O$ and $^{13}C/^{12}C$ in calcite and the ratio of deuterium to hydrogen (D/H) in fluid inclusions

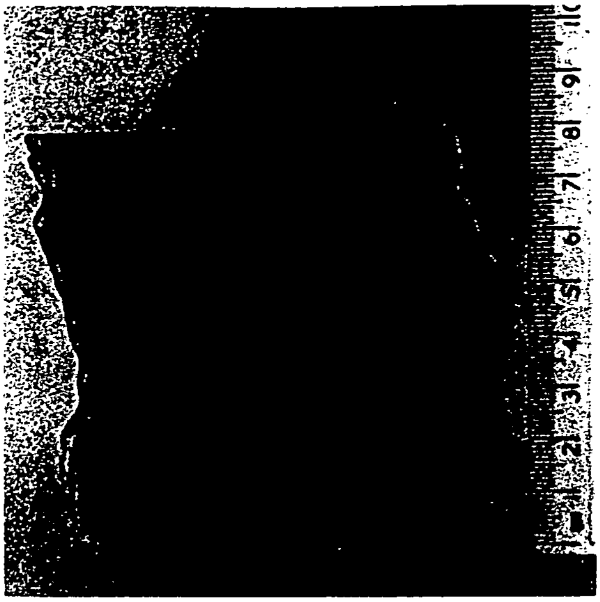

Fig. 7. Polished longitudinal section through portion of uniform-diameter stalagmite (LT) collected from Little Trimmer Cave, Mole Creek area. Convex-upwards growth layers are clearly seen.

can provide palaeoclimatic information (Hendy & Wilson, 1968; Harmon et al., 1979).

Four such stalagmites found in a broken condition in three different caves in the Mole Creek area were collected for isotopic studies. Multiple Th/U dates were obtained for LT and LX from Little Trimmer Cave, KK from Kubla Khan Cave, and LC from Lynds Cave. They are listed in Table 1 in stratigraphic order from base to tip. Further details are shown in Table 2.

The first three stalagmites in Table 2 appear to have grown at approximately constant rates. The lower height/age correlation coefficient for the KK specimen (Fig. 1) can be attributed to a combination of low uranium content and significant detrital contamination, as shown by the $^{230}Th/^{232}Th$ ratios (Table 1). Dating this stalagmite also yielded one inconsistent result (KK2) that has been disregarded because it is in total disagreement with all the other data. There was no geochemical or petrographic basis for rejection. The anomaly could possibly be due to a high organic content. As a check, samples KK 1.5 and KK 2.5 were dated (Fig. 2).

The LC stalagmite indicates a different growth history, and has a surface coating, which indicates that it has not been actively growing for some time. The upper portion is too recent to be dateable by the Th/U method, but the youngest date (LC3) indicates a minimum growth rate of 79 mm/ka above 45 cm—double the rate measured from 18 to 7 ka BP. Apparently it grew much more rapidly during the mild climatic conditions of the Holocene than during Late Glacial times when its growth was initiated. It appears that a uniform-diameter stalagmite cannot be expected to grow at a constant rate if a major climatic change occurs during its growth. This is contrary to the claim by Franke (1965) that for uniform-diameter stalagmites constant conditions of growth can be assumed. Tasmanian growth rates appear to be higher than those reported for North America. Harmon et al. (1975) reported average growth rates for seven uniform-diameter stalagmites and found a range of values from 2.3 to 58.5 mm/ka, with a mean value of only 20.6 mm/ka.

The relatively rapid growth rate of the Tasmanian specimens means that isotopic analyses to provide palaeoclimatic data can be obtained at short time intervals. For one of the stalagmites (LT) such analyses have been completed (Goede et al., in prep.).

CONCLUSIONS

Although Tasmania appears to offer a suitable environment for the rapid dissolution of carbonate rocks, the history of evolution of at least one of the more extensive karst caves appears to extend well beyond the range of $^{230}Th/^{234}U$ dating. Age determinations of speleothems in higher levels of multi-level cave systems enable maximum long-term rates of stream lowering to be calculated. These may be tentatively equated with rates of erosional lowering of the landscape in the general area.

A growth-frequency distribution in time of the 43 Tasmanian Th/U dates so far obtained shows that in general interglacial conditions are much more favourable than glacial conditions for speleothem deposition. However, a significant number of Tasmanian dates fall within the period of the Last Glacial Maximum (26 to 10 ka BP) which suggests

TABLE 2. Data on four uniform-diameter Tasmanian stalagmites.

Code No.	Height (cm)	Average diameter (cm)	No. of dates	Correlation coefficient (height/age)	Average growth rates (mm/ka)	Depositional time span (ka BP)
LT	142⁺	7	7	-0.98	43.2	109 - 76
LX	55⁺	9	3	-1.00	21.4	95 - 69
KK	107	9	7	-0.88	36.0	127 - 97
LC	0- 45	6	3	-0.99	40.0	18 - 7
	45-100*	6	-	-	> 79.0	7 - ?

⁺ Tip missing * Too young for Th/U dating that in Tasmania mean annual temperature is not the only factor restricting speleothem deposition.

Th/U dating can be applied to place age limits on clastic sediments in caves. Basal dates of stalagmites or flowstone growing on the sediments provide minimum ages, whereas detrital speleothems contained within the specimens can be used to provide maximum ages. In the Tasmanian environment such limits may be rather wide, as in the case of the Beginners Luck alluvium, partly because speleothem deposition was largely confined to the warmer climatic phases of the Quaternary.

Constant-diameter stalagmites were found to have growth rates ranging from 21 to 79 mm/ka with the highest value observed in the Holocene. Isotopic analyses, already in progress on some of these stalagmites, will enable the construction of detailed terrestrial palaeotemperature curves for Tasmania, although a complete record for the last 400 ka BP is unlikely to emerge.

ACKNOWLEDGMENTS

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Late Quaternary climatic change
Evidence from a Tasmanian speleothem

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ABSTRACT. This paper reports palaeotemperature studies on two segments of a uniform diameter stalagmite collected from a limestone cave in northern Tasmania. The calcite speleothem has been dated by a combination of C14 and ESR methods and is estimated to have been growing continuously between approximately 12 600 and 2800 BP.

The stalagmite was deposited under conditions of oxygen isotope equilibrium and variations in the O18/O16 ratio are believed to reflect changes in the mean annual temperature at the surface above the site. A profile of 39 $\delta^{18}O_c$ values is presented. A positive relationship between these values and mean annual temperature has been established for the area and this relationship is used to estimate the temperature during deposition.

On this basis the mean annual temperature during the period has varied between approximately 6.2 ° and 10.6 °C compared with a present day value of 9.5 °C. Temperatures were frequently higher than at present during the period 12 000 to 9300 BP but consistently lower since then. The lowest temperatures occurred approximately 3800 years ago. There is good evidence from elsewhere in the Southern Hemisphere that terrestrial temperatures were lower than today during the Late Holocene.

INTRODUCTION

The speleothem was collected from a high-level chamber in Lynds Cave, an active stream cave developed in Ordovician limestones. The cave is located in the Mole Creek area of northern Tasmania, Australia (41 ° 34' 20"S, 146 ° 13'40"E) (Fig. 1). The cave stream emerges from the base of a limestone cliff on the eastern bank of the Mersey River at an altitude of 300 m above sea level. The elevation of the area above the cave which supplies seepage water to the site is between 400 and 450 m. The area has a mean annual temperature of approximately 9.5 °C and a mean annual precipitation of 1500 mm with a pronounced winter maximum. The vegetation is wet sclerophyll forest with an understorey of rainforest species. The cave temperature at the collecting site was found to be 9.5 °C ± 1 °C.

The material consists of a stalagmite of uniform diameter (code: LY) which was found in a broken condition in two segments. The lower and upper segments have heights of 118 cm and 80 cm respectively. The two do not fit together, which indicates that a piece is missing. A care-

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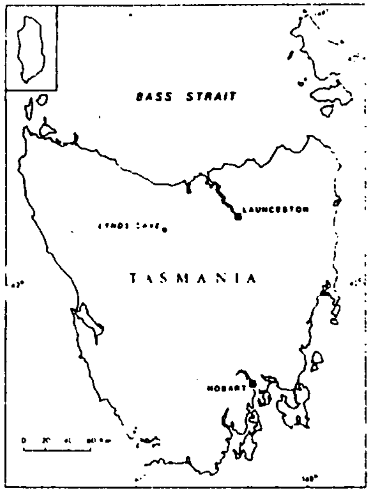

Figure 1. Location map of Lynds Cave.

ful search at the site failed to locate this segment and it is probable that it was either shattered when the stalagmite broke or removed from the cave.

OXYGEN ISOTOPE CONTENT AND TEMPERATURE

The stalagmite was sectioned longitudinally and one half set in plaster. Samples were taken at 50 mm intervals along the core using a 5 mm diameter drill. These were reacted with anhydrous H_3PO_4 under vacuum, using a conventional extraction line, to produce CO_2 gas that was then dried and purified prior to isotope analysis. All isotopic measurements of oxygen and carbon were made using a VG Micromass 602D mass spectrometer. Carbonate values were expressed in ‰ PDB and standardized to New Zealand standards TKL and K2. Water samples are standardized with respect to Vienna SMOW and ANU-C1 and are given relative to SMOW. The subscripts c, p and w denote calcite, precipitation and seepage water respectively.

The modern $\delta^{18}O_p$ and δD_p values and their seasonal variations are estimated for the area as monthly samples of precipitation were collected in 1979 at a site 3 km to the east of Lynds Cave entrance at an elevation of 460 m above sea level (Goede, Green and Harmon 1982). The values ranged from −0.8 to −6.4 ‰ $\delta^{18}O_p$ SMOW and from −2.2 to −37.3 ‰ δD_p SMOW. The weighted mean annual values are −4.82 ‰ and −26.7 ‰ SMOW respectively.

The secular relationship between $\delta^{18}O_c$ and temperature in the area is known from the appropriate altitude from another palaeotemperature study of a uniform diameter stalagmite (code: LT) from Little Trimmer Cave 3 km to the east (Goede, Green and Harmon, unpubl. ms). This 142 cm high stalagmite was deposited between 109 000 and 76 000 yrs BP according to U/Th dating. Eighteen fluid inclusion analyses (δD_w)

were carried out on this specimen in addition to measurements of $\delta^{18}O_c$. A highly significant positive statistical relationship was established between stratigraphically matched values of δD_w and $\delta^{18}O_c$.

$$\delta D_w(\mathrm{SMOW}) = 14\delta^{18}O_c + 22 \quad (1)$$

When values of δD_w are known, values of $\delta^{18}O_w$ can be estimated (Schwarcz, Harmon, Thompson and Ford 1976; Harmon, Schwarcz and Ford 1978; Harmon, Schwarcz and O'Neil 1979) using the present-day locally established relationship between them

$$\delta D_p(\mathrm{SMOW}) = 7\delta^{18}O_p(\mathrm{SMOW}) + 7 \quad (2)$$

Knowing both the $\delta^{18}O_w$ and $\delta^{18}O_c$ values of a number of stratigraphic horizons, the relationship between $\delta^{18}O_c$ values and temperature can be calculated using the formula

$$10^3 \ln \alpha_{c-w} = 2.78 \times 10^6 Ta^{-2} - 3.39 \quad (3)$$

where Ta is the temperature in °K (Harmon, Thompson, Schwarcz and Ford 1978). Using (1), (2) and (3) and assuming a present-day equilibrium value of $\delta^{18}O_c$ = −4.10 ‰ the following relationship is obtained

$$Tc = 4\delta^{18}O_c + 26 \quad (4)$$

where Tc is the temperture in °C. This should be regarded as a rough estimate based on the assumption that the slope and deuterium excess values in equation (2) have not deviated from present-day values in the past.

The positive relationship between oxygen isotope composition of calcite and temperature is unusual, but another well documented case of such a relationship has been made for two stalagmites collected from a cave on Vancouver Island (Gascoyne, Schwarcz and Ford 1980; Gascoyne, Ford and Schwarcz 1981). The reason for this phenomenon is believed to be the magnitude of the latitudinal shift in the moisture source areas accompanying climatic change and will be discussed in detail elsewhere (Goede, Green and Harmon, unpubl. ms.).

TEMPERATURE RECORD OF LYNDS CAVE STALAGMITE

Before palaeotemperatures can be determined from the Lynds Cave stalagmite three requirements have to be met:

1. It must be shown that the stalagmite was deposited under conditions of oxygen isotope equilibrium.
2. The isotopic composition of present-day calcite, deposited under conditions of oxygen isotope equilibrium, must be determined.
3. The speleothem must be dated to provide a reliable time scale.

Tests for oxygen isotope equilibrium

Two tests have been suggested to confirm deposition of calcite under equilibrium conditions (Hendy and Wilson 1968).

1. The absence of a strong positive correlation between values of $\delta^{18}O$ and $\delta^{13}C$ of samples taken at intervals along the longitudinal axis. Figure 2 confirms that this is indeed the case.

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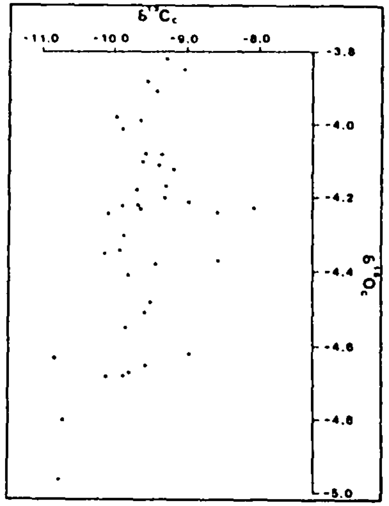

Figure 2. Scatter diagram of thirty-nine $\delta^{18}O_c$ and $\delta^{13}C_c$ values of samples taken along the longitudinal axis of the stalagmite.

2. Samples taken at intervals along a single growth layer outwards from the core should not show a progressive trend towards isotopically heavier values of $\delta^{18}O_c$ which correlate with a similar trend in $\delta^{13}C_c$ values. This was done by taking and analysing sets of seven samples from each of three growth layers A, B and C (Fig. 3). Again the conditions are met except for one unexplained anomalous pair of values for the first point along growth layer B.
Therefore the stalagmite is considered to have been deposited under conditions of oxygen isotope equilibrium and variations in $\delta^{18}O_c$ values should reflect variations in temperature.

Isotopic composition of modern calcite

To determine the oxygen isotope composition of calcium carbonate being deposited at present under conditions of oxygen isotope equilibrium, six actively growing straw stalactite tips were collected in the vicinity of the site. Since straw stalactites are also known to grow rapidly, this material is assumed to have been deposited during the last few years (Harmon, Schwarcz and Ford 1978). Each sample was analysed for $\delta^{18}O$ and $\delta^{13}C$ and the results are shown in Table 1.

Table 1. Isotopic analyses of straw stalactites in Lynds Cave.

Sample No.	$\delta^{18}O_c$(‰ PDB)	$\delta^{13}C_c$(‰ PDB)
OX - 21	-4.05	-8.57
OX - 22	-3.76	-6.86
OX - 23	-3.62	-7.19
OX - 24	-3.47	-6.90
OX - 25	-4.16	-7.82
OX - 26	-3.66	-6.72

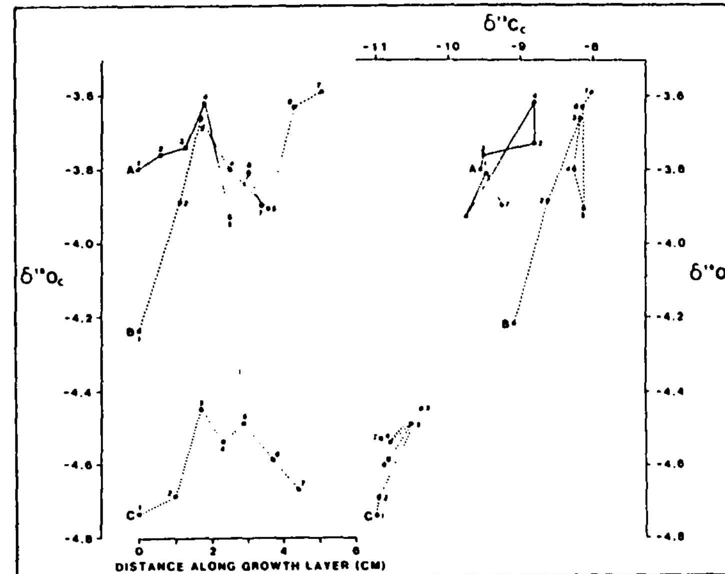

Figure 3. Variation of $\delta^{18}O_c$ with distance along each of three growth layers (on left) and with $\delta^{13}C_c$ for the same growth layers (on right).

The wide range of $\delta^{18}O_c$ values probably reflects a combination of two factors.

1. Values may vary because isotopically heavy summer precipitation may make a more significant seepage contribution to some straw stalactites than to others. In contrast, a fast growing stalagmite such as the one analysed in this paper is likely to obtain a high percentage of its carbonate deposition from seepage derived from winter precipitation under the prevailing climatic conditions.

2. Straw stalactites do not necessarily deposit calcite at oxygen isotope equilibrium. Non-equilibrium deposition is reflected in deposition of calcite that is isotopically heavier with respect to both oxygen and carbon.

The lowest values of $\delta^{18}O_c$ are therefore those which combine a dominance of depositing solutions derived from winter precipitation with deposition at or close to oxygen isotope equilibrium. Lowest values are shown by samples OX-21 and OX-25 which, as expected, also show the lowest values for $\delta^{13}C_c$. The present-day isotopic value of calcite deposited under oxygen isotope equilibrium conditions is believed to be close to the mean of these two samples, that is -4.10 ‰ $\delta^{18}O_c$.
An independent estimate of this value can be made when the isotopic composition of the seepage water and the cave temperature (9.5 °C) are known. The assumption is again made that seepage waters are derived from winter precipitation (weighted mean value $\delta^{18}O_p$ = -5.68 ‰ SMOW). This value is used together with the mean annual cave temperature in equation (3) to obtain a theoretical value for calcite of -4.20 ‰. This is in close agreement with the previously estimated value of -4.10 ‰.

While this value has been adopted, it must be remembered that it represents an average value for deposition taking place over several years prior to the collection of the material in August 1982. These years may, or may not, have been typical of present-day conditions of deposition. On the other hand, the samples drilled from the stalagmite core represent values that are averaged over a period of tens of years.

ESR DATING

Two methods were used to date the stalagmite: electron spin resonance (ESR) and C14 dating. Details of the ESR method are given in Ikeya (1978) while some of the problems involved in the application of the method are discussed by Wintle in Cook et al. (1982). As an initial step, the intensity of the free radical signal was measured for a large number of samples taken along the centre line of a longitudinal section using a 5 mm diameter drill. The samples were analysed on the JEOL JES-FE3X ESR spectrometer and the intensity values plotted against height (Fig. 4, left). The plot shows a steady increase in the strength of the signal with increasing age. Regression lines are shown for both the lower and upper segments. As a next step seventeen larger samples were taken and each sample subdivided into five sub-samples. Sub-samples were irradiated with incremental doses of γ-rays from a Co60 source. Then sub-samples of each set were measured individually on the ESR spectrometer and the intensity of the signal plotted against the γ-ray doses measured in rad. A regression line was fitted and the equivalent dose (ED) calculated for each sample. The ED values for the samples ranged from 125 to 1519 rad and increased progressively with increasing age.

The ED values represent the equivalent doses of natural radiation the samples have received after deposition of the calcite. These values were plotted against height and regression lines constructed for the relationships for both lower and upper segments of the stalagmite (Fig. 4, right). The scatter of points is much less than that of the plot of signal intensity against height suggesting that some of the scatter in the latter is due to inter-sample variations in sensitivity to radiation damage.

Random measurement errors involved in individual ED determinations are largely eliminated by using the values indicated by the regression lines for age determination at any point. The lines indicate that both the upper and lower segments of the stalagmite experienced constant growth rates if it is assumed that the annual dose rate has remained constant in time. However, the growth rate for the upper segment appears to have been more rapid than for the lower.

The ED can be used to determine the age at any point if the annual dose rate is known since

$$\text{Age (years)} = \frac{\text{Equivalent dose (rad)}}{\text{Annual dose rate (rad/year)}}$$

The annual dose rate consists of two components: the external and internal dose rates. The external dose is made up of radiation received by the sample from the surrounding environment and cosmic radiation. The internal dose rate is due to radioactive impurities within the sample and can be calculated if the concentrations of the elements U, Th and K are known.

The external dose rate was measured by placing a Rad-21 radiation dosimeter at the Lynds Cave site for a fortnight. The amount of radia-

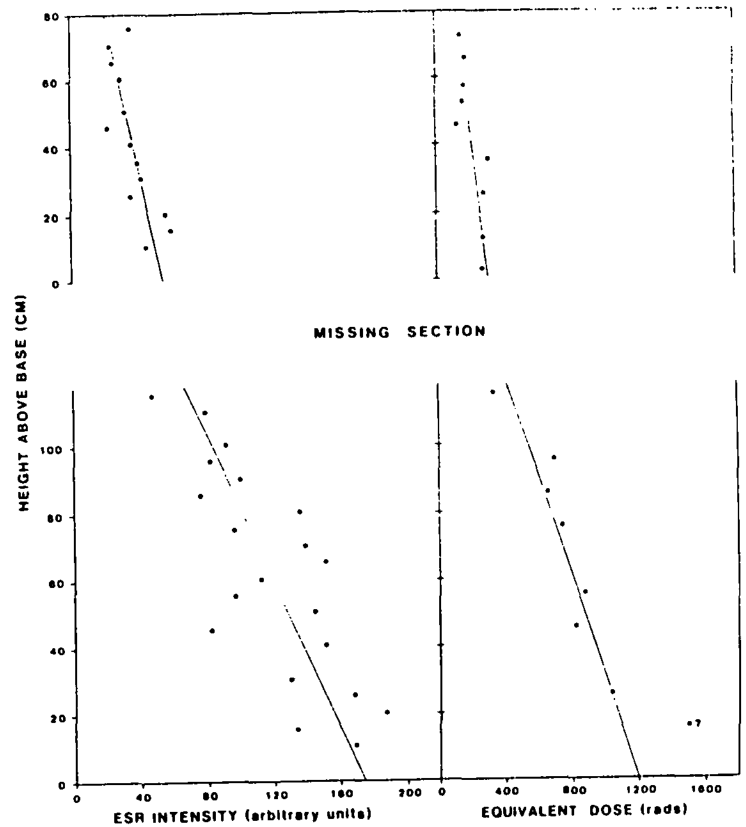

Figure 4. Variations of ESR signal intensity and ED as a function of height above base of stalagmite.

tion measured was equivalent to an external dose rate of 99 millirad/year but accuracy of measurement is low (± 20 %). To assess the internal dose rate, a series of sixteen samples was analysed by the CSIRO Division of Energy Chemistry using fluorimetric determinations. All, except the three basal samples, showed uranium concentrations below the detection limit of 0.035 ppm. The three basal samples contained an average of 0.1 ppm. U. Even this amount of uranium will give a dose rate of only 6.4 millirad/year (Aitken 1974). Concentrations of Th and K were not measured but are expected to be very low. The extremely small internal dose rate is very fortunate since it largely eliminates two major problems associated with ESR dating of calcite. They are:

1. Changes in internal dose rate with time since Th230 formed by the decay of U234 gradually increases the dose (Wintle 1978).
2. Problems caused within the sample by the concentration of uranium within small inclusions (Walton and Debenham 1980).

Since the external dose rate is small, a crude estimate of the annual

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dose rate of 100 millirad/year is assumed. This is at the lower limit of the range of annual dose rates estimated for speleothems by Ikeya (1978). The rate can be tentatively used to calibrate the age range of the stalagmite using the regression lines of ED values against height shown in Fig. 4, right.

Using the assumed dose rate the lowest segment was found to have grown between approximately 12 000 and 4100 yrs BP and the upper segment was deposited between approximately 3100 and 1270 yrs BP. These time ranges must be regarded as crude estimation, especially since ESR dating cannot yet be regarded as completely reliable (Wintle and Huntley 1982). However, it will be shown that ED determinations can be used in combination with C14 dating to provide a more accurate time-scale.

CARBON 14 DATING

Six samples were analysed: the base, middle and top of each of the two segments. Dating was carried out by the National Physical Research Laboratory in Pretoria. The C14 dates obtained are shown in Table 2.

Table 2. Carbon 14 age determination of LY stalagmite in Lynds Cave.

Sample No.	Anal. No.	Medium height above base (cm)	Apparent C14 age (yrs BP)
Lower Segment			
AG32	Pta-2972	2.5	14 500 ± 140
AG33	Pta-3198	57.5	13 000 ± 30
AG34	Pta-2975	112.5	10 300 ± 90
Upper Segment			
AG35	Pta-2976	3.0	8980 ± 90
AG36	Pta-3199	43.0	6400 ± 20
AG37	Pta-2979	78.2	5250 ± 70

The C14 ages cited in Table 2 are subject to a correction due to the reservoir effect. The C13 values of the stalagmite indicate that the apparent initial age could hardly have been less than 1000 years. On the other hand the theoretical maximum for this figure is 5500 years or one half-life of C14 (Hendy 1970). This initial age need not necessarily have remained constant with time, especially if the climate changed significantly. Furthermore, in order to obtain an estimate of the absolute time-scale the dates have to be calibrated to allow for temporal variations in the radiocarbon content of atmospheric carbon dioxide. Calibration tables have been published for conventional radiocarbon ages ranging from 10 to 7240 BP (Klein, Lerman, Damon and Ralph 1982).

We can estimate the reservoir effect from the upper segment of the stalagmite if two basic assumptions are made that during the period of deposition

1. the reservoir effect remained constant
2. the annual dose rate remained constant so that ED values bear a linear relationship to time.

The two C14 samples used are AG35 and AG37. The ED values corres-

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ponding to the median position of the two C14 samples can be determined from the regression line on Fig. 4, upper right. They are found to be 305 and 131 rad respectively. Therefore the ratio of absolute time between samples AG35 and AG37 should be 2.32.

Let the reservoir effect be x years. Different values of x between the range 1000 to 5500 years are applied to the C14 dates. For each value of x the dates are then converted to the absolute time-scale using the calibration tables and the time ratio is calculated. The value of x which most closely matches the AD ratio of 2.32 was found to be 2160 years and was adopted as the magnitude of the reservoir effect. This value is subtracted from the three C14 dates for the upper segment and they are then calibrated using the calibration tables to provide the time-scale in Fig. 5. The time-scale for the lower segment is constructed on the assumption that the resevoir effect has not changed. The calibration table cannot be used to convert the C14 ages to estimates of absolute time since the ages are beyond the range. Therefore the time-scale for the lower segment must be regarded as considerably less accurate. There appears to be a significant change in the growth rate of the stalagmite between the two segments. The growth rate of the lower segment is calculated as 26.2 cm/1000 year while the upper segment grew at a rate of 20 cm/1000 year. The rates of growth are very rapid compared with four other Tasmanian stalagmites whose growth rates have so far been determined (Goede and Harmon 1983).

PALAEOTEMPERATURE

The isotopic data are plotted against age in Fig. 5. It can be seen that between 12 600 and 9400 BP, values of $\delta^{18}O_c$ ranged between -4.35 and -3.82 ‰. During this period the average value was slightly above the modern value of -4.10 ‰. After 9400 BP there was a gradual decline in O18 until a minimum of 4.96 ‰ was reached at about 3800 yrs BP. The record terminates at approximately 2800 BP with O18 values well below present-day levels. The C13 values remain relatively uniform throughout between -8.1 and -10.8 ‰.

The $\delta^{18}O_c$ curve can be interpreted as reflecting variations in palaeotemperature. Equations (2), (3) and (4) are tentatively used to convert oxygen isotope values into estimates of palaeotemperature. The resulting palaeotemperature scale is shown on the top abscissa in Fig. 5. Between 12 600 and 9400 BP temperatures oscillated around the present-day mean annual temperature of 9.5 °C but reached a maximum of about 10.6 °C at 10 400 BP. Mean annual temperatures remained continuously below the present-day value after 9400 BP and reached a minimum value close to 6.2 °C at about 3800 BP. The mean annual temperature appears to have varied by as much as 4.4 °C during the growth period of the stalagmite.

Absolute temperature values should be treated with caution due to the assumption made in equation (2). However, relative temperature changes and temperature trends appear to be reliable.

DISCUSSION

The temperature pattern indicated by the oxygen curve suggests an early climatic optimum with temperatures intermittently higher than today between 12 000 and 9000 BP followed by a gradual decline below present-day temperatures through most of the Holocene until about 2800 BP when deposition ceased.

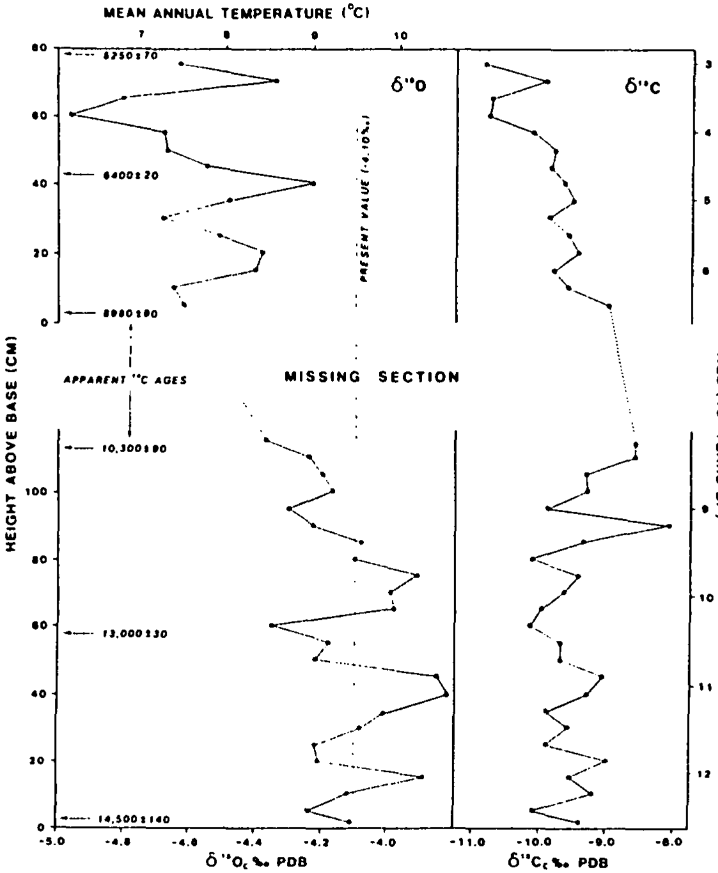

Figure 5. Temporal variations in the values of $\delta^{18}O_c$ and $\delta^{13}C_c$ with height above base of stalagmite. Mean annual temperature variation with time as well as median positions and apparent ages of six C14 dates are indicated.

The curve should be compared with palynological evidence obtained in southern Tasmania by Macphail (1979) who examined seven Holocene pollen sequences. Each was continuous and extended back at least 10 000 years. At one glacial lake site at 560 m (Lake Vera) Macphail found rapid forest encroachment occurring by 11 500 BP. He deduced that during the Early to Middle Holocene climates were wetter and possibly warmer than at present and suggested a 'climatic optimum' between 8000 and 5000 BP. During this phase cool temperate rainforest dominated by Nothofagus cunninghamii reached its greatest extent. During the Late Holocene there was an expansion of Eucalyptus dominated forests and an increase in shade-intolerant species.

Both isotope and palynological data suggest a change to cooler conditions during the later part of the Holocene. They differ significantly in their timing of the 'climatic optimum'. It must be remembered that while the isotope data reflect predominantly temperature changes, variations in the pollen diagrams are much more sensitive to changes in moisture availabiltiy and its seasonal distribution especially for sites at lower elevations. Detailed comparisons are also not possible at this stage since many of the pollen diagrams are poorly dated. The dating of the lower segment of the Lynds Cave stalagmite is uncertain because it assumes that the reservoir effect of the C14 dates is the same as for the upper segment.

Burrows (1979), working in the South Island of New Zealand (41 ° - 46 ° S), produced a radiocarbon dated chronology of glacial events and other cold climate phenomena during the last 12 000 years. He obtained fifteen C14 dates of less than 9000 BP related to glacial advances and other cold climate phenomena. All but three of these dates are younger than 5000 years. This points to a temperature decline during the Holocene.

Williams (1978) summarizes evidence from the Southern Tablelands of New South Wales that hillslopes were unstable and streams were aggrading between 4000 and 1500 BP. As possible causes he suggests lower temperatures, drier and windier conditions and changes in rainfall seasonality.

CONCLUSION

Evidence of Holocene climatic changes from various localities in the Southern Hemisphere appears to be broadly concordant with the trend of palaeotemperatures shown in Fig. 5.

The evidence from the oxygen isotope curve suggests that the mean annual temperature in northern Tasmania during the Holocene may have varied by some 4 °C from 1 ° above to 3 ° below the present-day value of 9.5 °C. The curve also indicates an early 'climatic optimum' between 12 000 and 9000 BP in contrast to palynological evidence which places it between 8000 and 5000 BP. However, in both cases the dating is inadequate.

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The six C14 age determinations were made by Dr JC Vogel of the National Physical Research Laboratory in Pretoria, South Africa. Dr MA Geyh of the Niedersächsisches Landesamt für Bodenforschung, West Germany, suggested the combined use of C14 and ESR analyses to provide a more accurate time-scale. Mr P Pakalns, of the CSIRO Division of Energy Chemistry at Lucas Heights, Australia, was responsible for the fluorimetric determinations of the uranium content of sixteen stalagmite samples. Samples of ANU isotope standards were made available by Mr A Chivas of the School of Earth Sciences at the Australian National University. Our sincere thanks to all of them.

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Electron spin resonance dating of Quaternary bone material from Tasmanian caves—a comparison with ages determined by aspartic acid racemization and C^{14}

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Fourteen bone samples are analysed to test the usefulness of equivalent dose (ED) determinations by electron spin resonance (ESR) as a rapid method of determining relative age and making an estimate of absolute age. ED values are compared with eight aspartic acid dates and two C^{14} dates. The latter are dates on charcoal found in close association with bone at archaeological sites. For samples less than 25 000 years old an excellent correlation is obtained when ED values are compared with dates obtained by the other two methods. The relationship suggests that ED values can be converted to estimates of bone age by assuming a mean annual dose rate of 0.1 rad/yr. Age determinations provide little evidence to support earlier suggestions that elements of the Late Pleistocene megafauna survived until the end of the Pleistocene. Bone material at some sites in the Florentine Valley and near Montagu appears to be much older than had previously been believed. Only one site (Main Cave, Montagu) containing megafaunal elements appears to be terminal Pleistocene in age but the possibility of reworking of megafauna material from nearby older sites cannot be excluded. ESR dating has considerable potential as an exploratory dating tool but can only be applied to dense, unaltered bone samples. Attempts to analyse five samples from Kutikina Cave in Western Tasmania were unsuccessful because of post-depositional contamination of the bone.

Key words: caves, Quaternary bone deposits, megafauna extinction, ESR dating, aspartic acid dating, C^{14} dating.

INTRODUCTION

Samples were taken mostly from material collected from a number of Tasmanian cave sites that were either excavated or sampled by P.F. Murray and A. Goede between 1975 and 1980. The material is held at the Tasmanian Museum and Art Gallery, Hobart. Sites excavated during the period have been described in the literature (Murray & Goede 1977; Goede *et al* 1978; Goede & Murray 1979; Murray *et al* 1980; Goede & Harmon 1983). In addition bone samples were collected and analysed from three recently discovered archaeological cave sites that were thought to be of Pleistocene age: Bone Cave in the Weld River Valley, Nanwoon Cave in the Florentine Valley and a sample found in an archaeological context in Nelson River Cave by K. Kiernan (Kiernan 1983). Five bone samples from a succession of occupation layers in Kutikina Cave (formerly Fraser Cave), Franklin River, were made available by D. Ranson but unfortunately proved to be unsuitable for ESR analysis due to post-depositional enrichment in iron compounds. This is unfortunate as the site is dated by multiple C^{14} analyses of associated charcoal (Kiernan *et al* 1983). Karst areas with caves that have yielded material for this study are indicated in Fig. 1.

ESR DATING

Electron spin resonance (ESR) was first considered as a possible dating method by Zeller (1968) who pointed out its potential for determining the age of geological materials. Ikeya (1975) applied the technique to the dating of calcite speleothems and subsequently to bone and gypsum (Ikeya 1978; Ikeya & Miki 1980). Garrison *et al* (1981) used ESR to date ancient flints; Ikeya and Ohmura (1981, 1983) to determine the age of fossil shells and corals. Sato (1982) applied it to planktonic foraminifera from deep sea cores. Attempts have also been made to use the technique to date intrafault materials (Ikeya *et al* 1982).

The ESR technique resembles thermoluminescence (TL) dating in that age estimates are based on a measure of radiation damage due to ionizing radiation. With the passage of time the

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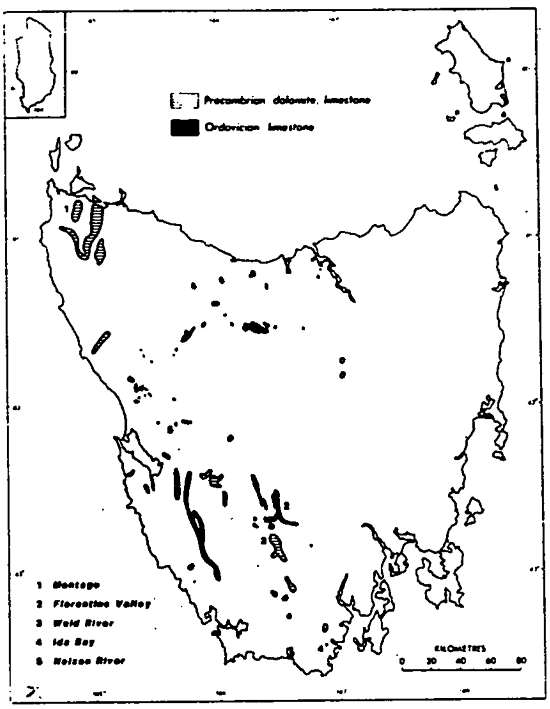

Fig. 1 Location of karst areas referred to in text.

substance to be dated accumulates lattice defects due to the impact of high energy particles. The presence of defects can be observed since they display characteristic absorption patterns at certain locations in the spectrum produced when the sample is exposed to a fixed microwave frequency in a varying magnetic field. The intensity of the defect signal, related directly to the amount of energy absorption, is a measure of the number of defects present.

The natural radiation dose received by a sample is a function of its age and consists of two components. The internal component is derived from the presence of radioactive impurities within the sample, principally isotopes of U, Th and K. The external dose is partly due to the presence of similar isotopes within the immediate environment of the sample and partly to the incidence of cosmic radiation.

The intensity of the defect signal measured on an ESR spectrometer is not a direct measure of the amount of radiation a sample has received. Different materials vary in their sensitivity to ionizing radiation. As long as the intensity of the defect signal has a linear response to radiation doses, the amount of radiation already received by the sample can be determined.

For analysis samples of dense bone weighing 1–5 g are scraped to remove weathered or otherwise altered outer layers. They are then crushed in a swingmill using a hardened chromesteel vessel. The method is used because it minimizes the generation of heat. The sample is then subdivided into five sub-samples of approximately equal weight. One is retained in an unirradiated condition while the others are exposed to a radiation source (Co60) with length of exposure increasing at approximately equal intervals of time.

Irradiation dose rates have been within the range of 6.5–9.0 rad h^{-1}. The irradiated samples are stored for at least a fortnight prior to measurement to allow fading of any unstable ESR signals produced by irradiation. Weighed portions of each sub-sample are analysed on a JEOL JES-FE3X ESR spectrometer (Fig. 2). All measurements were made on samples placed in the centre of the cavity and at ambient temperatures with a modulation of 100 KHz with a 2-gauss peak-to-peak amplitude. Manganese could not be used as an internal standard since none could be detected in the samples. Using an external manganese standard the value of the g factor was determined as 2.002. The value is identical to that measured by Ikeya and Miki (1980).

When the intensity of the defect signal of each sub-sample has been measured, the values are adjusted for variations in weight and are plotted against the artificial radiation dose (ARD). A linear relationship is usually found (Fig. 3). A regression line is fitted and extrapolated to intercept the dose axis. The intercept represents the equivalent dose (ED). The ED value gives an estimate of the ARD which produces a defect signal intensity equivalent to that produced by the natural radiation dose during the life of the sample.

In order to determine the age of a sample, the assumption is made that the sample and its immediate environment have remained a closed system with respect to radioactive isotopes. The best estimate of age can be made if the external dose is measured at the excavation site and the internal dose is calculated based on the U, Th and K content of the sample. Since such an approach was not feasible for this study we assume here that all bone deposits we have sampled have received similar radiation dose rates. Aspartic acid and C^{14} dating were used to calibrate the ED values in order to provide an estimate of the annual dose rate.

ASPARTIC ACID DATING

Aspartic acid is one of a number of amino acids that occur in the proteins of living organisms. In

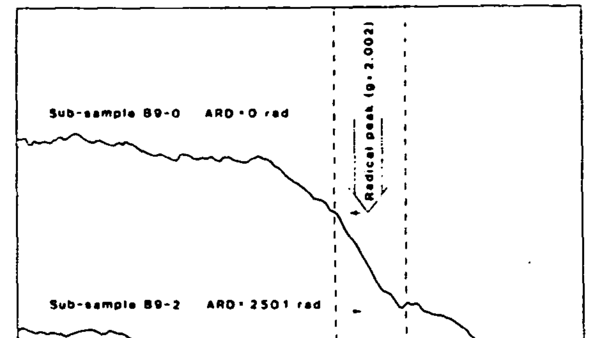

Fig. 2 ESR spectrographs of sub-samples of fossil bone (sample B9) exposed to different artificial radiation doses. The height of the radical peak (ESR intensity) provides a relative measure of the amount of radiation damage.

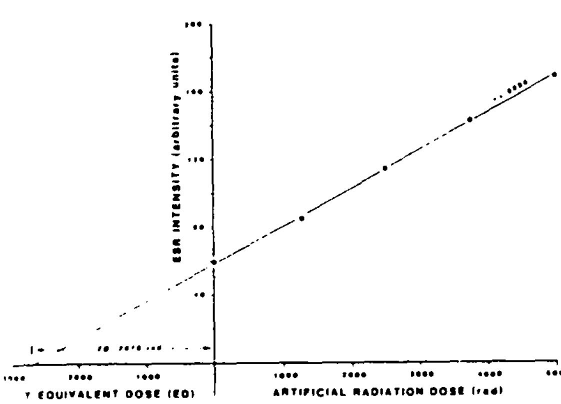

Fig. 3 ESR intensity of sub-samples of B9 plotted against the artificial radiation dose (ARD). The equivalent dose (ED) is determined by the intercept on the horizontal axis.

higher organisms the proteins contain only L-amino acids. After death the amino acids, including those in bone, undergo a gradual change to the equivalent D-amino acids. This process is known as racemization. In fossil bone both L- and D-amino acids are usually found. The D/L amino acid ratio increases with sample age until an equilibrium mixture is produced. Each amino acid has a characteristic racemization rate but since it is a chemical reaction the rate varies with temperature (Bada, in press).

The D/L ratio can be used to estimate the age of a bone sample only if the temperature history of the bone is known or can be estimated. Since aspartic acid racemization rates are strongly temperature dependent (Bada & Protsch 1973; Bada & Schroeder 1975) a calibration sample is needed when dating Upper Pleistocene deposits in order to estimate the average temperature depression during the last glacial event. Such a sample should have an age of approximately 17 000 to 25 000 years BP (Bada & Deems 1975). A macropodid long bone fragment was provided by Dr S. Bowdler from an archaeological excavation in Cave Bay Cave on Hunter Island, off the NW coast of Tasmania. It came from the lowest occupation horizon dated on associated charcoal at 22 750 ± 420 BP (ANU-1498) (Bowdler 1975, 1977). The reliability of the C^{14} date is enhanced because it is one of a sequence of four dates between 14 000 and 23 000 BP with good agreement between the stratigraphic and chronological evidence. The calibration sample was found to have a D/L aspartic ratio of 0.16. When the assumption is made that the bone has been exposed to equal time periods of Holocene and Late Pleistocene temperature conditions, it can be deduced that mean annual temperatures during the Late Pleistocene were approximately 6° C lower than at present. This is in good agreement with other evidence (Colhoun 1983; Kiernan 1983). Details of the calibration calculations are found in Schroeder and Bada (1973) and McCullough and Smith (1976).

The Cave Bay Cave site has a present day mean annual temperature estimated at 12° C and without modification provides a suitable calibration sample for the dating of bones from Pleisto Scene Cave and Main Cave (Montagu area). These sites are relatively close to Cave Bay and have similar elevation and temperature characteristics. The other four sites are all in the Florentine Valley. They are at an elevation of some 400 m and are much further S. Spot temperature measurements indicate a present day cave temperature of approximately 8° C. Therefore the Cave Bay Cave calibration rate has to be

Table 1 Cave locations and age estimates

Cave name and area	Latitude	Longitude	Altitude (m)	Estimated ESR age	Other age estimates	Published source
Nanwoon Cave (JF-333), Florentine Valley	42°42′	146°25′	400	7 200		
Main Cave (MU-201), Montagu	40°51′	144°54′	20–40	13 000	13 000 (A)*	Murray & Goede (1977)
Bone Cave (W-3), Weld River	42°50′	146°28′	400	15 000	16 200 (C)	
Nelson River Cave (N-X1), Nelson River	42°7′	145°41′	300	19 000		Kiernan (1983)
Boomer Cave (JF-91), Florentine Valley	42°34′	146°28′	400	20 000		
Site P, Beginners Luck Cave (JF-79), Florentine Valley	42°34′	146°28′	400	21 000	21 000 (A) 20 650 (C)	Murray *et al* (1980)
Site G, Titans Shelter (JF-97) Florentine Valley	42°35′	146°28′	400	27 000	40 000 (A) 14 310 (C)	Goede & Murray (1979)
Site E (lower), Titans Shelter (JF-97), Florentine Valley	42°35′	146°28′	400	44 000		Goede & Murray (1979)
Site F, Titans Shelter (JF-97), Florentine Valley	42°35′	146°28′	400	49 000		Goede & Murray (1979)
Site O, Beginners Luck Cave (JF-79), Florentine Valley	42°34′	146°28′	400	61 000		
Site M, Beginners Luck Cave (JF-79), Florentine Valley	42°34′	146°28′	400	63 000	80 000 (A)	Murray *et al* (1980)
Un-named cave (JF-155), Florentine Valley	42°32′	146°27′	400	97 000	30 000 (A)	
Exit Cave (IB-14), Ida Bay	43°29′	146°51′	60	270 000	>112 000 (I)	Goede & Harmon (1983)
Chamber B, Pleisto Scene Cave (MU-206), Montagu	40°51′	144°54′	20–40	310 000	130 000 (A) 130 000 (A) 110 000 (A)	Murray & Goede (1977)

*(A) = aspartic acid date; (C) = C14 date on charcoal; (I) = ionium date.

adjusted to this temperature using the procedures given by Bada *et al* (1974). The use of adjusted rate constants involves a degree of reduction in the precision of the dates. It should be kept in mind that racemization dates have an uncertainty of ± 25% or better.

Aspartic acid dating requires samples of approximately 10 g of dense, unaltered bone. All samples were processed using the procedure outlined by Bada and Protsch (1973) and Masters and Bada (1978). The results of aspartic acid racemization dating are shown in Table 1.

ANALYTICAL RESULTS

They are summarised in Table 1. In Fig. 4 the ED values obtained by ESR analysis have been plotted against age estimates for the same deposits obtained by aspartic acid dates on bone and C^{14} dates on associated charcoal. One minimum age, based on a $^{230}Th/^{234}U$ age determination of flowstone calcite overlying a bone-bearing deposit has also been included. Annual dose rates of 0.1 and 0.2 rads are indicated in the figure by dashed lines since Ikeya and Miki (1980) found annual dose rates within this range for bones in limestone caves. For ED values less than 2500 rad, good correlation exists with aspartic acid and C^{14} ages. The points are found to cluster closely around the line representing a dose rate of 0.1 rad/year. This dose rate was used to estimate ESR ages shown in Table 1. Ages are rounded off to the nearest 100 years where the estimated age is between 1000 and 10 000 years, to the nearest 1000 years where the age is between 10 000 and 100 000 years and so forth.

DISCUSSION OF SITES

Nanwoon Cave, Florentine Valley

This is an archaeological site containing stone artifacts and bone. It has not been excavated but was presumed to be Pleistocene. A bone sample (B16) was collected for ESR analysis and yielded an estimated age of 7200 years BP. The site may be early Holocene in age rather than Pleistocene.

Main Cave, Montagu

A sample of bone was collected from the site by Murray and Goede (1977), but it has not been

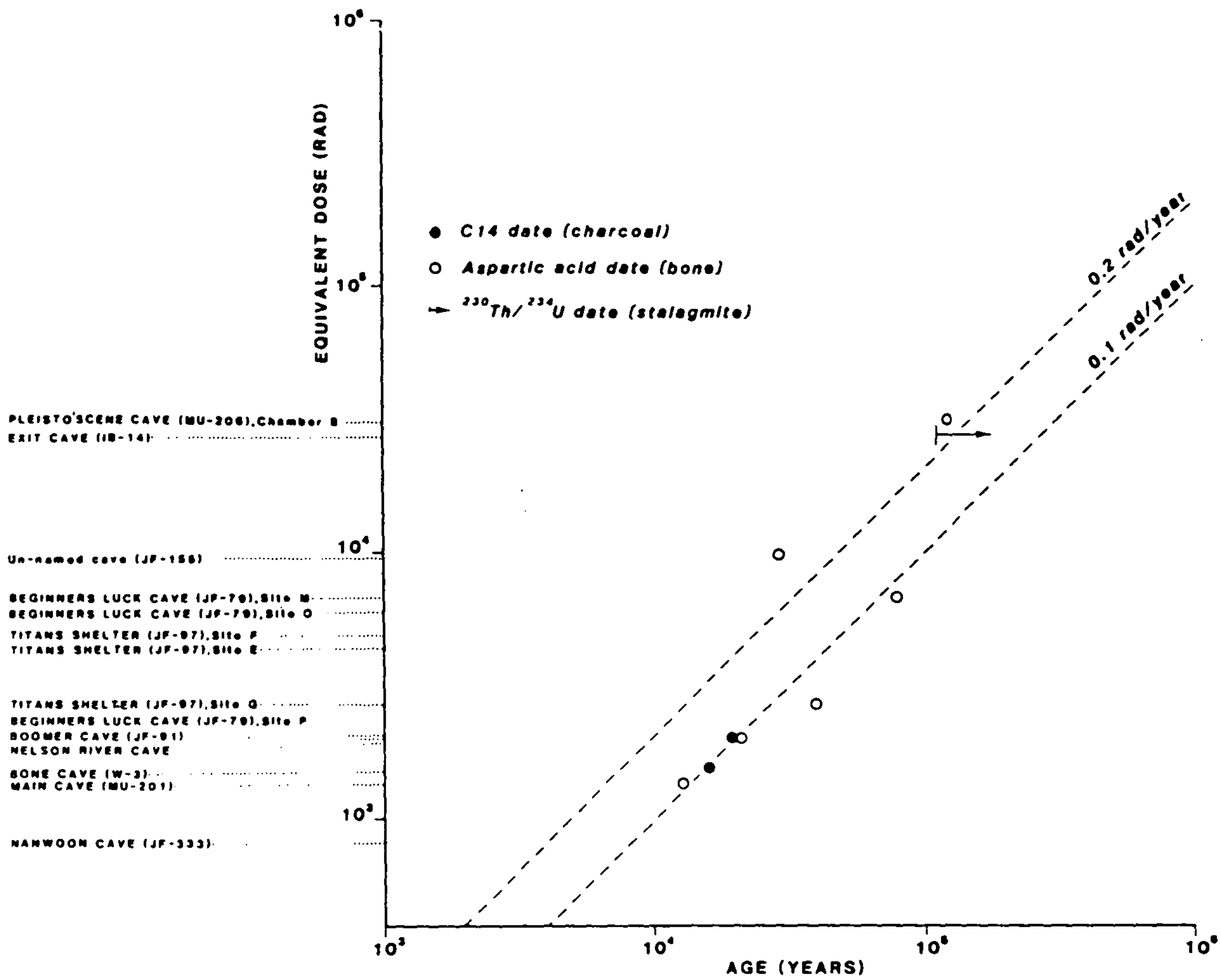

Fig. 4 Equivalent doses (ED's) of fossil bone samples plotted against age determinations made by C^{14} aspartic acid and ionium dating techniques. The line representing an annual dose rate of 0.1 rad year^{-1} was used to convert ED values to age estimates.

excavated. Both the aspartic acid (AG26) and the ESR data (B10) suggest an age of 13 000 years BP. Extinct species recorded from the site are *Sthenurus occidentalis* and *Zaglossus* sp. While it may indicate late survival of these species, it must be kept in mind that the site is quite close to Chamber B in neighbouring Pleisto Scene Cave. Reworking of older bone is a possibility.

Bone Cave, Weld River

This archaeological site is in a dolomite shelter cave. Stone artifacts and bone were found in a shallow trench eroded by running water at the back of the cave. A sample of a charcoal was collected from a section exposed in the trench at a depth of 10–15 cm below the surface. A C^{14} date yielded an age of 16 200 + 1200–1100 years BP (SUA-2104). An ESR date yielded an age of 15 000 years BP (B7). The site appears to be Late Pleistocene.

Nelson River Cave, Western Tasmania

The geomorphology and stratigraphy of this limestone cave has been described by Kiernan (1983). The dated bone comes from the upper few centimetres of his unit 1—a thick deposit of alluvial sediments. The author reports the presence of split and burnt bones at this site, suggesting that the deposit is associated with human occupation of the cave. ESR dating has yielded an age of 19 000 years BP (B17). This fits in well with Kiernan's interpretation of unit 1 as an outwash gravel belonging to the maximum of the last glaciation (Margaret Glaciation). In the valley of the Dante Rivulet 10 km to the N drifted wood in proglacial silts immediately below the outwash gravels of the Margaret Glaciation has been C^{14} dated at 18 800 $\pm$ 500 years BP (ANU-2533) (Kiernan 1983). Aboriginal occupation at this time is known from the Franklin River Valley to the S (Kiernan *et al* 1983).

Boomer Cave, Florentine Valley

This limestone cave site has been sampled but not excavated. The sample includes bone attributed to *Macropus titan* (Murray, pers. comm.). The ESR data suggests an age of 20 000 years BP (B18). The site is within 200 m of Beginners Luck Cave, where site P is known to be of similar age and also contains *Macropus* cf. *titan* (Murray *et al* 1980).

Site P, Beginners Luck Cave, Florentine Valley

This is an archaeological site which has been described in detail elsewhere (Goede & Murray 1977; Murray *et al* 1980). It consists of a partly cemented mudflow deposit containing abundant bone, some stone artifacts and charcoal. A bone fragment belonging to *Macropus rufogriseus* yielded an ESR age of 21 000 years BP (B4). This is in excellent agreement with an aspartic acid date on similar bone which also gave an age of 21 000 years BP (AG20). Charcoal from the same deposit yielded an age of 20 650 $\pm$ 1790 years BP (GaK-7081), again in excellent agreement.

Site G, Titans Shelter, Florentine Valley

The site has been described by Goede and Murray (1979) as a bone-bearing alluvial fan deposit. Extinct Pleistocene faunal remains occur throughout the deposit and at least five species are represented. The bone has been reworked and appears to have originated from a carnivore's den. It could be older than the sediment in which it is found. Charcoal from the site has yielded an age of 14 310 + 2970 − 2160 years BP (GaK-6875) which seems surprisingly young. The possibility that the charcoal is intrusive cannot be excluded.

The site has yielded an ESR age of 27 000 years BP and an aspartic acid age of 40 000 years BP (AG27). While not in close agreement both dates indicate a much greater age than is indicated by the C^{14} date. This date has been quoted by Goede, Murray and Harmon (1978) as evidence of late Pleistocene survival of megafauna in the Florentine Valley. It is now clear that either the bone is much older than the alluvial deposits in which it is found or the charcoal in the deposit is intrusive.

Site E (lower) and Site F, Titans Shelter, Florentine Valley

The two sites represent bone accumulations in a deposit built up by gravitational movements of angular limestone fragments provided by physical weathering and roof-fall. It has been interpreted as a cryoclastic deposit that accumulated under cold and probably dry conditions (Goede & Murray 1979). An age coinciding with the last glacial maximum (18 000–20 000 years BP) has been tentatively suggested. The two sites have yielded ESR ages of 44 000 years BP (sample B7, site E) and 49 000 years BP (sample B8, site F). The two dates indicate a significantly older age than the ESR date of bone material found at site G but are comparable with the aspartic acid date at this site. The stratigraphic interpretation of the site by Goede and Murray (1979) is that breccias found at sites E and F overlie the alluvial fan deposits at site G. If this is correct the fan and breccia deposits would appear to have accumulated in quick succession.

Sites O and M, Beginners Luck Cave, Florentine Valley

The two sites are in close proximity and at both bone is found on the surface of the cave floor. At site M the bone has been cemented to the substrate by subsequent carbonate deposition. Organic carbon residue of bone at site M dated by C^{14} has yielded an age of 14 450 $\pm$ 250 years BP (Goede & Murray 1977). The same site has yielded an aspartic acid date of 80 000 years BP (AG19) (Murray *et al* 1980) and an ESR date of 61 000 years BP (B5). A bone sample from site O has yielded an ESR date of 63 000 years BP (B6). The C^{14} date on bone at site M is likely to be erroneous. The two sites appear to be similar in age.

Un-named cave (JF-155), Florentine Valley

The bone deposit overlies an alluvial deposit which on the basis of the degree of weathering of dolerite clasts can be correlated with the Beginners Luck alluvial phase (Goede & Harmon 1983) to which the authors assigned a probable age range of 50 000–75 000 years BP. Aspartic acid dating yielded an age of 30 000 years BP (AG28) while a sample analysed by ESR yielded an age of 97 000 years BP (B19). Agreement between the two dating methods is poor. If the age range estimate of the underlying alluvium is correct it would appear that the ESR date is in error. The bone content of the site has not been studied but appears to consist predominantly of *Macropus rufogriseus*. No extinct fauna has been identified.

Exit Cave, Ida Bay

A single large bone was dated by ESR at 270 000 years BP (B3). It is believed to have come from a complex debris cone found in a passage drained by a small tributary stream within this very extensive cave system. The material appears to have originated from a series of vertical shafts that rise towards the surface. The site has been described by Goede and Harmon (1983). A minimum age of 112 000 ± 3000 years BP was obtained for the deposit by ionium dating of a 7 cm high stalagmite that had grown on an undissected part of the cone surface. The ESR date indicates that the cone deposits may be considerably older than the minimum age previously indicated.

Chamber B, Pleisto Scene Cave, Montagu

The site is located in a small dolomite cave and contains a bone breccia that accumulated as a debris fan from a roof fissure that is now sealed. Excavation of the deposit has yielded a rich fauna including the extinct species *Sthenurus* sp., *Protemnodon anak, Macropus titan, Zaglossus robusta, Thylacoleo carnifex, Palorchestes* sp. and ?*Zygomaturus* (Murray & Goede 1977). A minimum age was established for the deposit by C^{14} dating of the oldest layer of overlying flowstone yielding an apparent age of 17 670 ± 180 years BP (Pta-2506). This data is subject to a correction due to the reservoir effect and may be too old by several thousand years. A minimum age of about 15 000 years appears to be indicated. Goede *et al* (1978) suggested a maximum age for the deposit based on an ionium date of 20 000 ± 4000 years BP for a detrital stalactite collected from the floor of nearby Chamber A.

Three aspartic acid dates were obtained from the Chamber B deposit yielding ages of 130 000, 130 000 and 110 000 years BP (AG14, 17 and 18). These ages must be regarded as very approximate because of the difficulty of estimating the temperature history of the bone over such a long period. A tentative date of 310 000 years BP (B2) was obtained by ESR. This is also not a good age estimate because the irradiation doses given to the sub-samples made only a small difference to the intensity of the defect signal. Both dating methods, while providing markedly different estimates of age, are in agreement that the material excavated from the debris fan in Chamber B is very much older than the 15 000–20 000 years age that has previously been suggested. We now believe that the significance of the ionium date from Chamber A (Goede & Harmon 1983) has been misinterpreted.

CONCLUSION

Equivalent dose estimates obtained by ESR analysis have been successfully calibrated over the last 21 000 years using C^{14} and aspartic acid dating. We find that the annual dose rate for bone in Tasmanian cave deposits is approximately 0.1 rad year^{-1}. This rate can be used to obtain estimates of ages using ESR when other dating methods cannot be applied.

When the equipment is available the method has the advantage of being rapid and inexpensive. Multiple dates are readily obtained from one site and should improve the precision of estimating the ED value and lead to a better estimate of age. Where a deposit contains bone of different ages, ESR should provide a suitable method for distinguishing the age fractions.

Another advantage of ESR analysis is that it requires only a small quantity of material—no more than 1 g of dense, unaltered bone. This means that it can be applied readily to bone belonging to extinct species without sacrificing much skeletal material.

There are considerable advantages in dating the bone itself rather than associated materials. The relatively few ESR and aspartic acid dates reported in this paper illustrate this. Much of the evidence claimed by Goede *et al* (1978) favouring the late survival of megafauna can now be refuted. In particular we have established the very considerable age of the bone content of Chamber B in Pleisto Scene Cave near Montagu. Bone material found at sites E and F in Titans Shelter and sites M and N in Beginners Luck Cave, all in the Florentine Valley, has also been shown to be significantly older than expected.

The site in Main Cave near Montagu remains an enigma. Both ESR and aspartic acid dating are in close agreement on an age of 13 000 years BP yet *Zaglossus* sp. and *Sthenurus occidentalis* are recorded. Reworking of older material and its incorporation at this site is a possibility as it is close to Chamber B in Pleisto Scene Cave where much older material is now known to occur. Surveys suggest that the distance between the two sites is no more than 10 m. Although there is at present no physical connection between Main Cave and Pleisto Scene Cave the two are obviously part of a single system.

Not all fossil bone is suitable for ESR dating. Five samples from Kutikina Cave in the Franklin River valley proved impossible to date due apparently to post-depositional impregnation of the bone by iron oxides.

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Late Pleistocene palaeotemperature record from a Tasmanian speleothem

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Multiple $^{230}Th/^{234}U$ age determinations on a uniform diameter calcite stalagmite from a Tasmanian cave show that it was deposited between 109 000 and 76 000 years BP at a constant rate of 4.3 cm per 1000 years. Except for the first 9000 years, deposition occurred under conditions of oxygen isotope equilibrium enabling it to be used for palaeotemperature studies. Measurements of $^{18}O/^{16}O$ ratios of calcite and D/H ratios of fluid inclusions indicate that mean annual temperatures at the site were nearly always lower than at present from 100 000 to 76 000 BP. A positive relationship is found between mean annual temperature and the $^{18}O/^{16}O$ content of calcite. This is uncommon and represents the first such relationship recorded from the Southern Hemisphere. The stalagmite shows evidence of having grown during two distinct temperature phases. From 100 000 to 97 000 years BP mean annual temperatures were between 4°C and 6°C compared with a present day value of 9.5°C. At about 97 000 years BP there was a rapid transition to milder conditions with mean annual temperatures oscillating around 8°C until the record terminates at 76 000 years BP.

Key words: speleothems, isotopes, radiometric dating, palaeotemperatures, climatic change.

INTRODUCTION

Speleothem growth depends on a supply of carbonate saturated seepage water with a P_{CO_2} exceeding that of the cave atmosphere. Loss of CO_2 occurs by diffusion and deposition takes place, usually in the form of calcite. The high P_{CO_2} in the solution is usually due to previous contact with CO_2-enriched air in the soil zone. Two alternative processes of dissolution are involved which have relevance to the isotopic composition of speleothems. Dissolution of carbonate may take place in an 'open system' where the solution remains always in contact with an excess of CO_2 gas. Alternatively, dissolution of carbonate takes place in a 'closed system' with the water remaining isolated from a gas phase until its emergence in a cave (Hendy 1971).

Evaporation is not usually involved in the deposition process in caves located in humid environments because of the constant high level of relative humidity of the cave atmosphere. Exceptions occur close to cave entrances.

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Deposition of speleothems normally occurs under conditions of near constant temperature that approximate to the mean annual temperature at the surface. In the Little Trimmer Cave monthly temperature measurements during 1979 showed a mean annual temperature of 9.5°C with a range of approximately 1°C (Goede *et al* 1982).

In what follows all δD and $\delta^{18}O$ isotopic measurements relating to water are expressed in ‰ relative to SMOW while $\delta^{18}O$ and $\delta^{13}C$ measurements on calcite are given as ‰ relative to PDB. The following subscripts are used throughout the text: p, precipitation; w, seepage water; fl, fluid inclusion water and c, calcite.

The calcite initially precipitated from a saturated solution will have a $\delta^{13}C$ value depending on whether dissolution took place under open system or closed system conditions, as well as on the P_{CO_2}, temperature and pH of the precipitating solution. At 10°C, and assuming soil $\delta^{13}C$ gas = −24‰, the first calcite to be deposited would have a $\delta^{13}C_c$ value of between −12 and −10‰ for a 'closed system' solution and −13.2 ‰ for an 'open system' solution. If the rate of loss of CO_2 is slow the calcite deposited will be in oxygen isotope equilibrium with water.

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Hendy and Wilson (1968) have suggested two tests for deposition under oxygen isotope equilibrium conditions:

(i) The absence of a strong positive correlation between values of $\delta^{18}O_c$ and $\delta^{13}C_c$ of samples taken at intervals along the longitudinal axis. In the present case such correlation is evident only in the basal 35 cm and this portion of the stalagmite was rejected for palaeotemperature analysis.

(ii) When multiple samples are taken at intervals along a single growth layer outwards from the core there should be no progressive trend towards isotopically heavier values of $\delta^{18}O_c$ correlating with a similar trend in $\delta^{13}C_c$ values. These conditions are satisfied and the Little Trimmer stalagmite above 35 cm is shown to have been deposited under conditions of oxygen isotope equilibrium. One growth layer shows a progressive trend towards isotopically lighter values for both $\delta^{18}O_c$ and $\delta^{13}C_c$. This may be due to rapid deposition from a supersaturated solution.

Under conditions of isotopic equilibrium, changes in $\delta^{18}O_c$ values along the growth axis of the stalagmite are controlled by three major factors (Harmon *et al* 1978):

(i) Change in the temperature of deposition of the calcite. The depositional temperature inside the cave approximates to the mean annual surface temperature at the site. At 10°C, the fractionation effect for $\delta^{18}O$ is $-0.24^{o}/_{oo}/^{o}C$.

(ii) Change in the isotopic composition of seawater. This is due to the accumulation of ^{18}O-depleted glacial ice on land and is estimated to cause an increase of at least $0.1^{o}/_{oo}$ in the value of $\delta^{18}O_p$ for every 10 m drop in sea-level (Shackleton & Opdyke 1973).

(iii) Change in the isotopic composition of precipitation caused by: changes in climatic conditions at the site of evaporation and precipitation; and changes in the geographical location of moisture source areas as weather patterns adjust to changes in climate.

Changes in factors i and ii cause cave calcite deposited during cold phases to become enriched in ^{18}O while factor iii opposes these effects. The fact that a large majority of stalagmites examined so far show a negative relationship between $\delta^{18}O_c$ values and past temperatures indicates that in most situations the combined effects of factors i and ii outweigh factor iii (Harmon *et al* 1978). The only well documented case for a positive relationship has been made for two stalagmites from Vancouver Island (Gascoyne *et al* 1980, 1981). It will be shown that such a positive relationship also exists in the Litter Trimmer stalagmite.

The speleothem used is a 142 cm tall uniform diameter stalagmite with tip and basal portion missing. It was collected in a broken condition from a cave (Little Trimmer Cave) developed in folded Ordovician limestone near Mole Creek, northern Tasmania, Australia (146°14′41″E, 41°34′21″S) at an altitude of 460 m above sea level (Fig. 1). The site is some distance from the nearest entrance and has a high humidity atmosphere without significant air movement.

All values used in this study are based on measurements made at the Central Science Laboratory, University of Tasmania. Isotopic measurements made on water samples are standardized with respect to Vienna SMOW and ANU-C1 while measurements made on carbonate are expressed in $^{o}/_{oo}$ relative to PDB and standardized with respect to New Zealand standards TKL and K2. Comparisons of these with US standards can be found in Blattner and Hulston (1978) and Landis (1983).

The present day isotopic compositions of precipitation, cave drips and actively forming

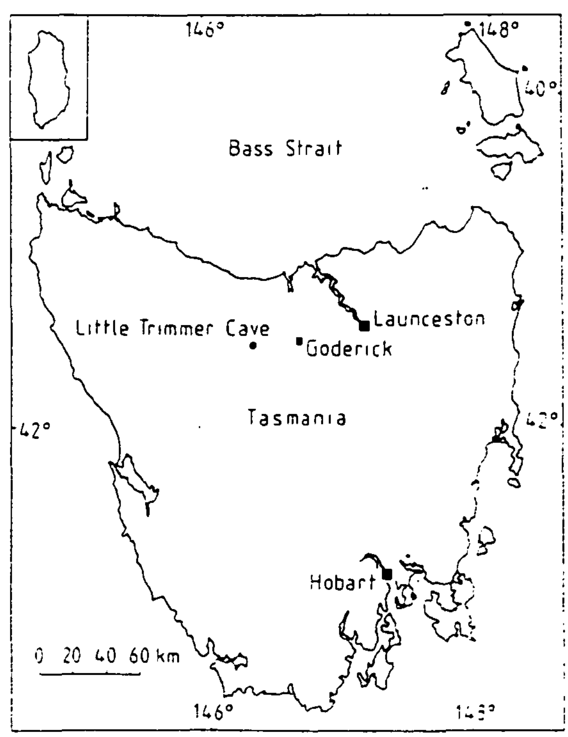

Fig. 1 Location of cave site and nearest climatological station.

speleothems at this site are well known (Goede *et al* 1982) and only salient aspects are summarized here.

Monthly sampling of precipitation and seepage water was carried out during 1979. The weighted means of precipitation for the year were $\delta^{18}O_p$ = $-4.8^o/_{oo}$ and δD_p = $-27^o/_{oo}$. The statistical relationship (RMA: reduced major axis) between δD_p and $\delta^{18}O_p$was

$$\delta D_p = 7.0\ \delta^{18}O_p + 6.9\ (r = 0.94) \qquad (1)$$

To determine the present day composition of speleothem material, calcite was collected from two plastic funnels used to gather cave drip water during 1979. The drip water site was located only a few metres from the site where the Little Trimmer stalagmite had been collected. Multiple isotopic analyses of the calcite yielded an average value of $-3.75^o/_{oo}$ $\delta^{18}O_c$. Using this value and the weighted mean oxygen isotope composition of precipitation the temperature for equilibrium deposition of calcite can be calculated.

The equilibrium constant for the system calcite-water was originally determined by O'Neil *et al* (1969) but has subsequently been modified following the revision of the value for CO_2-H_2O fractionation from 1.0407 to 1.0412 (O'Neil *et al* 1975) on which its derivation depends. The modified equation (Harmon *et al* 1978) is given as:

$$10^3 \ln K_{c-w} = 2.78\ 10^6 T_A^{-2} - 2.89 \qquad (2)$$

where K_{c-w} = $(^{18}O/^{16}O)_c/\ (^{18}O/^{16}O)_w$ and T_A is the absolute temperature. Seepage water at this stage is assumed to have an isotopic composition identical to that of weighted mean annual precipitation. For the purpose of this calculation $\delta^{18}O_c$ values are first converted to SMOW (Friedman & O'Neil 1977) using the expression

$$\delta_{SMOW} = 1.03086\ \delta_{PDB} + 30.86 \qquad (3)$$

Using the weighted mean annual $\delta^{18}O_p$ value of $-4.82^o/_{oo}$ in equation 2 a cave temperature of 11.3°C was calculated. This is rather higher than the measured mean annual cave temperature of 9.5°C. However it appears highly probable that winter precipitation makes a greater contribution to cave drips than summer precipitation because of reduced evapotranspiration during winter. Taking the extreme case where only winter precipitation contributes, equation 2 was recalculated using the weighted mean winter $\delta^{18}O_p$ value of $-5.68^o/_{oo}$. This yielded a calculated cave temperature of 7.8°C, lower than the observed temperature.

Deposition of modern calcite at oxygen isotope equilibrium is confirmed if it is accepted that winter precipitation makes a greater contribution to cave seepage than summer precipitation. Knowing the oxygen isotope composition of calcite deposited at oxygen isotope equilibrium ($-3.75^o/_{oo}$) during 1979 as well as the cave temperature, the mean isotopic composition of seepage water during the year is calculated as $\delta^{18}O_w$ = $-5.26^o/_{oo}$. Using equation 1, δD_w = $-30^o/_{oo}$ is obtained. These values are adopted as representative of the present day isotopic composition of seepage water at the site. They are in good agreement with mean values of monthly cave drip samples ($\delta^{18}O_w$ = $-5.04^o/_{oo}$, δD_w = $-29^o/_{oo}$) from a nearby drip site during 1979.

Radiometric dating

The stalagmite has been dated by means of seven $^{230}Th/^{234}U$ age determinations (Table 1, Fig. 2) following the procedures of Harmon *et al* (1975) and is observed to have been deposited at a constant rate of 4.32 cm per 1000 years between 109 000 and 76 000 years BP. The time scale in Fig. 2 has been determined by regression analysis of distance above base against radiometric age in order to reduce the random error involved in individual age determinations (Goede & Harmon 1983).

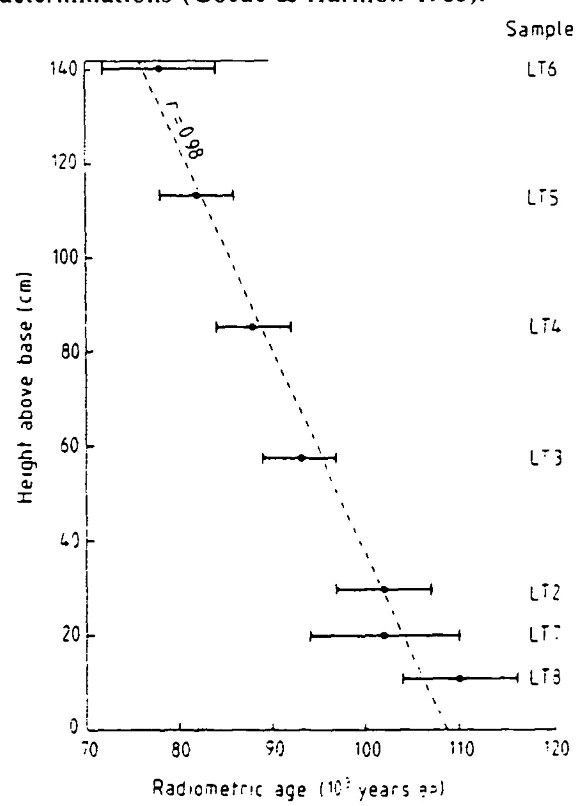

Fig. 2 Regression of distance above base on radiometric age for Little Trimmer stalagmite (LT) from a cave near Mole Creek, Northern Tasmania.

Table 1 Uranium concentrations, isotope activity ratios, and calculated age for the Little Trimmer (LT) stalagmite.

Sample	Median position above base (cm)	U p.p.m.	$\frac{[^{230}Th]}{^{234}U}$	$\frac{[^{234}U]}{^{238}U}$	$\frac{[^{230}Th]}{^{232}Th}$	Age (years $\times$ 10^3)
LT7	10.8	0.9	0.68 ± 0.02	2.28 ± 0.02	62	110 ± 6
LT8	19.75	0.9	0.66 ± 0.03	2.19 ± 0.01	200	102 ± 8
LT2	29.5	1.1	0.66 ± 0.02	2.37 ± 0.01	44	102 ± 5
LT3	57.5	0.8	0.62 ± 0.02	2.35 ± 0.02	145	93 ± 4
LT4	85.5	0.8	0.59 ± 0.02	2.35 ± 0.01	234	88 ± 4
LT5	113.5	0.6	0.57 ± 0.02	2.02 ± 0.01	100	82 ± 4
LT6	140.5	0.7	0.54 ± 0.03	2.51 ± 0.02	229	78 ± 6

As a further check on the reliability of these dates another age determination was obtained on sample LT7 using the $^{231}Pa/^{235}U$ technique. An age of 97 + 42 − 29 was obtained (Ivanovich pers. comm.). While less precise, this date shows concordance with the corresponding $^{230}Th/^{234}U$ date.

METHODS

For sampling purposes the stalagmite was sectioned longitudinally (Fig. 3). Samples were then taken at regular intervals along the core using a 5 mm diameter drill. CO_2 gas was prepared from the calcite by reaction with anhydrous H_3PO_4 under vacuum in a conventional extraction line, and $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios determined on a VG Micromass 602D mass spectrometer. Analytical

Fig. 3 Polished longitudinal section through portion of the Little Trimmer stalagmite.

data are reported in Fig. 4. Analytical precision is ± 0.1‰. In order to establish whether or not deposition had occurred under conditions of isotopic equilibrium, sets of seven samples were drilled from each of three growth layers with a 2 mm diameter drill.

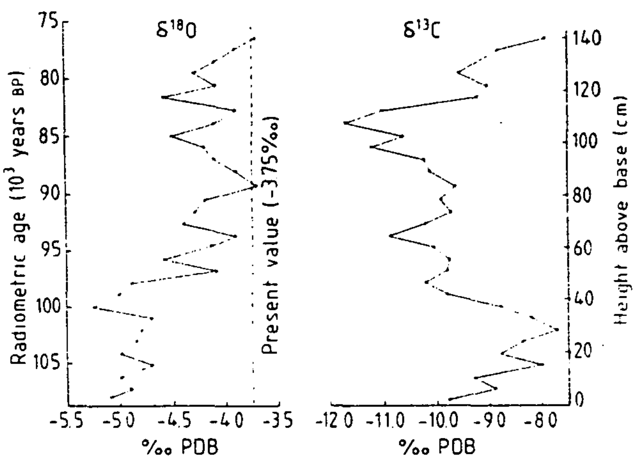

Fig. 4 Temporal variations in the values of $\delta^{18}O_c$ and $\delta^{13}C_c$ obtained from the Little Trimmer stalagmite.

Determination of the D/H values of fluid inclusions (δD_w) requires much larger speleothem samples. Samples were cut as 5 mm thick slices from the central core at the same stratigraphic positions as samples drilled for $\delta^{18}O_c$ analysis. The difference in sample size means that exact stratigraphic equivalence between values of δD_{fi} and $\delta^{18}O_c$ cannot be expected. D/H ratios were measured on the same instrument as $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios but with an analytical precision of ± 2‰.

An estimate of palaeotemperature can be made using equation 2 provided that the isotopic composition of seepage water at the time of deposition is known or can be estimated. Such water is preserved in fluid inclusions. Inclusion water could have continued to exchange oxygen isotopes with the surrounding calcite following its incorporation in the deposit (Schwarcz *et al* 1976). Therefore the usual procedure is to measure the D/H ratio since the surrounding calcite contains no hydrogen that could have exchanged with the hydrogen in the inclusion water.

The relationship between δD_p and $\delta^{18}O_p$ is known (equation 1). Since the seepage water shows no signs of fractionation when compared with the weighted mean isotope values of precipitation, the relationship given by equation 1 can be used to estimate the original $\delta^{18}O$ value of the seepage water.

The initial method used to extract fluid inclusion water from the samples was one of crushing following the method of Harmon *et al* (1979). The technique frequently did not yield sufficient inclusion water from subsequent reduction and analysis. Out of 10 samples attempted, only four were successfully measured. The second method is the decrepitation technique developed by Yonge (1981, 1982). The samples are heated to 700°C under vacuum causing decomposition of calcite to CaO while generating CO_2 and releasing inclusion water. This technique showed important advantages over crushing. Three grams of calcite invariably yielded sufficient water for analysis leaving enough material for at least one duplicate analysis. Where these were attempted they showed a satisfactory degree of reproducibility of results.

Palaeotemperature analysis

In Fig. 4 isotopic data are plotted against age. Disregarding the basal 35 cm, the three points between 100 000 and 97 000 years BP have values of $\delta^{18}O_c$ that oscillate around $-5‰$. At 97 000 years BP a rapid change occurs and values oscillate around $-4.1‰$ until the record terminates at 76 000 years BP. With only two exceptions, the oxygen isotope content of the samples is isotopically lighter than calcite deposited at present ($-3.75‰$).

Because of the possibility of postdepositional exchange of oxygen in the fluid inclusions, the determination of the relationship between $\delta^{18}O_c$ and temperature requires the analysis of the δD_{fi} content of fluid inclusions at points along the axis of the stalagmite (Schwarcz *et al* 1976; Harmon *et al* 1978, 1979). Eighteen samples were successfully analysed, together with two samples of modern speleothem material from another cave in the vicinity of the site (Fig. 5). A positive linear relationship is observed:

$$\delta D_{fi} = 13.9\, \delta^{18}O_c + 1.6 \; (r = 0.85) \qquad (4)$$

Applying Student's *t*-test the correlation is found to be highly significant ($P << 0.001$). A positive linear relationship clearly exists. Since δD values have a positive relationship with mean annual temperature, a similar relationship must also exist between $\delta^{18}O_c$ and mean annual temperature.

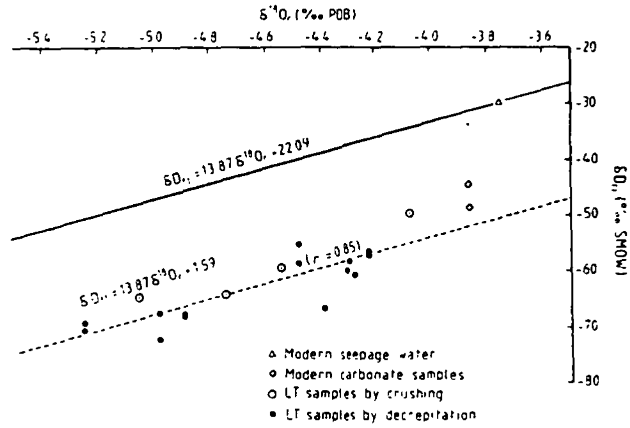

Fig. 5 Positive relationship of δD_w and $\delta^{18}O_c$ values for 18 samples and two modern samples. Solid line shows adjustment of relationship for systematic error. Regression lines: adjusted (——); calculated (----).

The regression line indicates a significantly lighter value for δD_w of present day water ($-50‰$) in equilibrium with present day calcite ($-3.75‰$ $\delta^{18}O$) than has been either calculated previously ($-30‰$ δD) or observed from monthly drip samples ($-29‰$ δD); (Fig. 5). It is important to note that two modern speleothem samples are similarly affected and that both methods of fluid inclusion water extraction yield similar values.

The results are in excellent agreement with those of Yonge (1982) who carried out very detailed studies of fluid inclusions in North American speleothems. He made a comparison between δD_w and δD_{fi} of waters extracted from associated modern speleothems. He found that calcite-bound waters were lighter than associated seepage waters by an average of $22.1 \pm 3.9‰$. Yonge originally suspected the presence of structural or oriented water as a possible cause but investigation by infrared and neutron diffraction methods failed to reveal the presence of such water. A possible explanation is that water within calcite is fractionated by adsorption onto crystal surfaces.

Close agreement between the present results and those of Yonge indicates that a local phenomenon is not being dealt with.

The error is a systematic one and assuming that the amount by which measurements are in error is constant over the range of measured values the observed regression line can be adjusted. This has been done by allowing it to pass through the point representing the present day values of δD_w and $\delta^{18}O_c$. The regression equation becomes:

$$\delta D_{fl} = 13.9\ \delta^{18}O_c + 22.1 \qquad (5)$$

This relationship is used in the calculation of palaeotemperatures.

In order to use equation 2 to calculate palaeotemperatures, δD values have to be converted to the corresponding $\delta^{18}O$ values. The relationship between δD and $\delta^{18}O$ is well known (Dansgaard 1964) and has the general form:

$$\delta D = X\ \delta^{18}O + d_0 \qquad (6)$$

where d_0 is referred to as the deuterium excess. In the Dansgaard formula $X = 8.0$ and $d_0 = +10°/_{00}$ (meteoric water line). For the following reasons this was not used for conversion:

(i) Values for X vary significantly depending on geographic location. They range from 8.3 for ice and snow analyses from Victoria Land, Antarctica (Drewry 1980) to 3.5 for precipitation at Darwin, Northern Territory, Australia. Values of $X < 7.5$ are a common feature of island stations (Dansgaard 1964).

(ii) Harmon and Schwarcz (1981) have found that palaeotemperatures for five areas of east-central North America and Bermuda, calculated using the meteoric water line, were clearly too low during late Pleistocene glacial periods. In some instances the calculated temperatures fell below 0°C. Since speleothem formation must cease at 0°C this is clearly an impossibility. The authors attributed this to temporal changes in d_0. Independent evidence of such changes has recently been demonstrated in Antarctica where Jouzel *et al* (1982) studied a deuterium excess profile from the Dome C ice core in Antarctica spanning some 32 000 years. They found that during the last glacial maximum the value of d_0 fell to 4 compared with 8.3 during the past 7500 years. This suggests that during cold periods d_0 may have been significantly lower also at Mole Creek but it is unlikely that it would ever have been less than 4.

Since the calculations leading to palaeotemperatures are highly sensitive to variations in the values of X and d_0, and the use of the meteoric water line was found to yield improbably low temperatures for the Little Trimmer Cave site, it was felt that the locally derived relationship (equation 1) would be the most appropriate one to use. Moreover, in view of the uncertainties of the constancy of the value of d_0 in time, palaeotemperatures were calculated for two relationships:

(A) $\delta D = 7\delta^{18} + 7$ (from equation 1)

(B) $\delta D = 7\delta^{18}O + 4$

where (B) represents a limiting case of (A) under full glacial conditions.

Palaeotemperatures were calculated for relationships (A) and (B) for each of three values of $\delta^{18}O_c$: -3.70, -4.42 and $-5.25°/_{00}$. They represent the maximum, mean and minimum values of 31 analyses obtained from the stalagmite. Results are shown in Table 2.

The calculations required for Table 2 make use of equation 2 and enable the establishment of a secular relationship between $\delta^{18}O_c$ and mean annual temperature (T) for both relationships A and B:

$$\text{For A} \quad \delta^{18}O_c = 0.26T - 6.22 \qquad (7)$$

$$\text{For B} \quad \delta^{18}O_c = 0.25T - 6.55 \qquad (8)$$

They have been used to calculate temperature scales A and B in Fig. 6. Scale A should be used where $\delta^{18}O_c$ values are close to the present day value. Scale B may give a closer approximation when $\delta^{18}O_c$ values are very negative. It must be realized that the calculated palaeotemperature values can only be regarded as crude estimates and that evidence of trends and abrupt changes has more significance than the absolute values.

In order to judge the plausibility of the calculated palaeotemperatures the likely range of temperatures in Tasmania during the last 120 000 years must be considered from other evidence. The present mean annual temperature at the site (9.5°C) is likely to

Table 2 Palaeotemperatures (°C) calculated for three values of $\delta^{18}O_c$ using two different relationships between δD_w and $\delta^{18}O_w$.

Relationship	Value of $\delta^{18}O_c$ −3.70	−4.42	−5.25	Temperature range	$\Delta\delta^{18}O_c/°C$
(A) $\delta D = 7\delta^{18}O + 7$	9.6	6.8	3.6	6.0	+ 0.26
(B) $\delta D = 7\delta^{18}O + 4$	11.4	8.5	5.3	6.1	+ 0.25

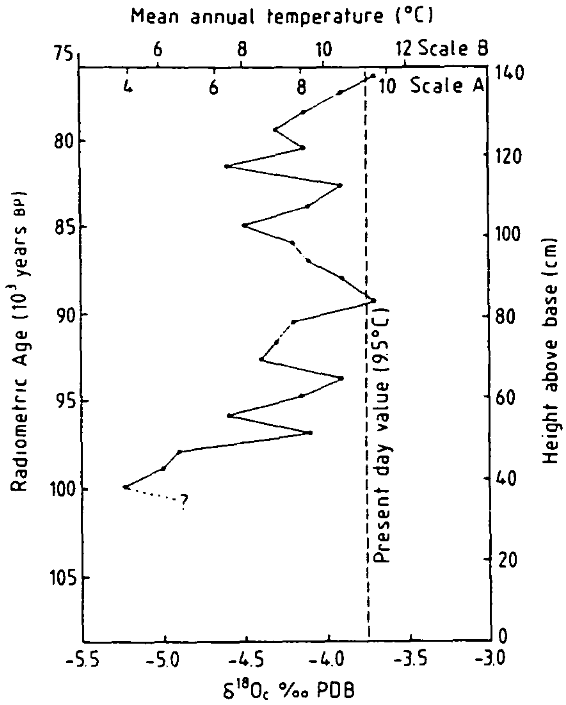

Fig. 6 Mean annual palaeotemperatures calculated for the Little trimmer (LT) stalagmite using the relationships $\delta D = 7\delta^{18}O + 7$ (Scale A) and $\delta D = 7\delta^{18}O + 4$ (Scale B).

be close to the maximum value recorded during this period and has probably been exceeded only during the early Holocene (Colhoun 1983a). Similarly, the evidence for late Pleistocene glaciation in Tasmania indicates that the greatest extent of glacier ice occurred at approximately 18 000 ± 2000 years BP. Detailed mapping of ice limits on the West Coast Range (Kiernan 1980) has enabled Colhoun (1983b) to estimate a temperature lowering of 6.8°C for this area at the last glacial maximum. The present site area has a more continental location and at that time its continentality would have been further increased by the exposure of most of the seafloor of Bass Strait (Jennings 1971). A lowering in excess of 7°C appears indicated. The maximum amount of temperature lowering cannot have been more than 9.5°C since no evidence of permafrost is found in the area despite the fact that during the penultimate glaciation ice cover was considerably more extensive in Tasmania than during the last glacial maximum (Kiernan 1980). An estimate of temperature lowering of 8 ± 1°C at 18 000 ± 2000 years BP is indicated.

The period of time from 100 000 to 76 000 years BP clearly reflects climatic conditions generally cooler than the present (Fig. 6) but the palaeotemperature range for the period must have been significantly less than 8°C. Both methods of palaeotemperature calculation presented in Table 2 provide values well within these limits.

An alternative but rather crude method to calibrate the $\delta^{18}O_c$ values with respect to palaeotemperature is to use isotopic information from deep-sea cores, provided that two basic assumptions are made:

(i) The mean annual temperature at Mole Creek during the last glacial maximum was approximately 8°C lower than it is today.

(ii) There is a linear relationship between terrestrial palaeotemperatures in Tasmania and $\delta^{18}O_c$ values determined on planktonic foraminiferal tests from a deep-sea core at a similar latitude in the Southern Hemisphere.

The core selected was RC11-120 (79°52'E, 43°31'S) collected from a depth of 3135 m. Values of $\delta^{18}O_c$ were determined by Hays *et al* (1976a) and vary from a modern value of +1.95 to +3.35‰ at the last glacial maximum.

The core record cannot of course be regarded as a palaeotemperature record of ocean water in the area since most of the variation in $\delta^{18}O_c$ is due to accumulation and melting of glacier ice (Shackleton & Opdyke 1973). Nevertheless, temperature and ice volume changes must be closely related as long as lag effects between temperature changes on the one hand and changes in glacier ice volume and the mixing time of the oceans on the other are kept in mind.

Over the period 100 000 to 76 000 years BP deep-sea core RC11-120 contains eight $\delta^{18}O_c$ determinations which yield an average value of +2.5‰. On the assumption that the glacial-interglacial temperature difference at Mole Creek of 8°C corresponds to a range from +1.95 to +3.35‰ in the deep-sea core and knowing that present mean annual temperature at the site is 9.5°C the average mean annual temperature for the period can be calculated as 6.1°C. This corresponds to an average $\delta^{18}O_c$ value for the stalagmite of −4.42‰ compared with a modern value of −3.75‰. Assuming a linear relationship between mean annual temperature and the oxygen isotope composition of the stalagmite one finds that $\delta^{18}O_c$/°C = 0.20‰. Considering the small number of data points from the core and the uncertainties involved in its dating (Hays *et al* 1976b) this is in reasonable agreement with the values obtained in Table 2.

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DISCUSSION

The Little Trimmer stalagmite is interesting in that it shows a positive relationship between temperature and $\delta^{18}O_c$ values. The relationship presented in this report has been confirmed by application to a Holocene stalagmite from another cave in the Mole Creek area (Goede & Hitchman 1984). The resulting palaeoclimatic curve shows a gradual temperature decrease during the Holocene that can be verified by palynological data (Macphail 1979).

The only other well documented case for a positive relationship has been made for two stalagmites from Vancouver Island (Gascoyne *et al* 1980, 1981). Both sites represent temperate marine west coast climates between 40° and 50° latitude. These unusual relationships are apparently due to a very large interglacial-glacial change in the isotopic composition of precipitation. The most probable explanation would be a marked poleward shift in the oceanic moisture source due to much stronger latitudinal airflow patterns during glacial periods. However, it should be noted that the temperate west coast site of Waitomo in the North Island of New Zealand has yielded a negative relationship (Hendy & Wilson 1968) and a similar relationship has also been inferred for a cave site in the South Island of New Zealand by Wilson *et al* (1979).

Duplessy *et al* (1970) presented a $\delta^{18}O_c$ profile of a stalagmite from Aven d'Orgnac in southern France. The profile shows a dramatic drop in the values of $\delta^{18}O_c$ at about 97 000 years BP and this was interpreted by the authors as an abrupt cooling event. The same event has been reinterpreted subsequently by Emiliani (1971) as evidence of rapid warming. The Little Trimmer Cave palaeotemperature curve indicates rapid warming at exactly this time and supports Emiliani's interpretation. A negative relationship between temperature and $\delta^{18}O_c$ values in the Aven d'Orgnac stalagmite is thus indicated.

Correlation of the speleothem palaeotemperature curve with the marine isotope chronology is problematical. The curve clearly falls within marine isotope stage 5. Unfortunately, dating of the deep-sea record is not very satisfactory. The timescale is interpolated between high sea-level stands, dated by uranium series analyses of raised corals, on the dubious assumption that the rate of sedimentation is constant. The high sea-levels of isotope sub-stages 5a, 5c and 5e are dated at approximately 82 000, 105 000 and 125 000 years BP (Bradley 1985). Each is preceded by a period of rapid warming. The speleothem curve shows temperature maxima at 89 000 and 76 000 years BP preceded by rapid warming at about 97 000 years BP. The most probable interpretation is that the speleothem curve is equivalent to marine isotope sub-stages 5a and 5b.

The Little Trimmer Cave speleothem curve shows that the mean annual temperature had fallen to between 4° and 5°C at about 100 000 years BP. During the next 3000 years there was a rapid rise to 8°C. In the remaining period the temperature oscillated about this value with two isolated peaks when temperature approximated to that of the present day.

Several authors have presented evidence for short periods of rapid cooling during the period of time covered by the growth of the Little Trimmer stalagmite (Dansgaard *et al* 1972, Kennett & Huddleston 1972, Flohn 1979). A number of possible causal mechanisms have been suggested including the occurrence of Antarctic ice surges (Wilson 1969, Hollin 1972). The nature and location of the present site would make it eminently suitable to detect such events but no evidence has been found. It may well be that the points are too widely spaced (> 1000 years) and that more closely spaced sampling would provide such evidence.

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ELECTRON SPIN RESONANCE ANALYSIS OF MARINE GASTROPODS FROM COASTAL ARCHAEOLOGICAL SITES IN SOUTHERN AFRICA

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INTRODUCTION

The Klasies River Mouth (KRM) caves are rock shelters and sea caves located on the southern coast of the Cape Province of South Africa at approximately 34°7′ south and 24°24′ east (figure 1). The caves have been developed in mid-Palaeozoic Table Mountain quartzite. They are relict features and have been eroded by waves at the base of now degraded coastal cliffs that marked the limit of wave activity when the sea level stood relatively higher than at present. The KRM1–1a complex and KRM1b relate to a sea level of approximately + 7 m while KRM2 and KRM5 both relate to a sea level of about + 18 m.

The sites have attracted considerable archaeological interest not only because they appear to have preserved some of the earliest remains of *Homo sapiens* but also because they document important changes in Middle Stone Age (MSA) technology and raw material usage and some of the earliest evidence for the systematic exploitation of coastal resources (Singer and Wymer 1982). The macro-mammal faunal samples were analysed by Klein (1976) and on this information, Binford (1984) has argued that the MSA occupants were using the caves as convenient shelter near a water hole for the scavenging of larger-body-size animals. The quantities of marine food resources incorporated in the deposits and the shifts between coastal and terrestrial-type economies evident in the sequence, however, have been seen by Deacon (1985) to indicate functioning as a base camp in the conventional sense.

The cave sites first became widely known due to the excavations of Wymer and Singer in 1967–68 (Wymer and Singer 1972) although detailed analyses of the material were not published until later (Voigt 1973, Singer and Wymer 1982, Binford 1984). In 1984–85 a sampling programme was undertaken by the Archaeology Department of the University of Stellenbosch under the direction of Professor J. H. Deacon.

Sixteen samples were submitted by Deacon to the authors for analysis. Of these fourteen were collected from KRM1, KRM1a and KRM5 sites in 1984–85. The remaining two samples were obtained by courtesy of the South African Museum from collections of material from the 1967–68 excavation. Details of the thirteen samples analysed are shown in table 1. The other three were not used because insufficient material was available. None of the shells were collected from ash layers and further care was taken to avoid material showing signs of having been burnt. Only columellae and opercula were used in the analysis as their massive nature makes them less prone to contamination by percolating water.

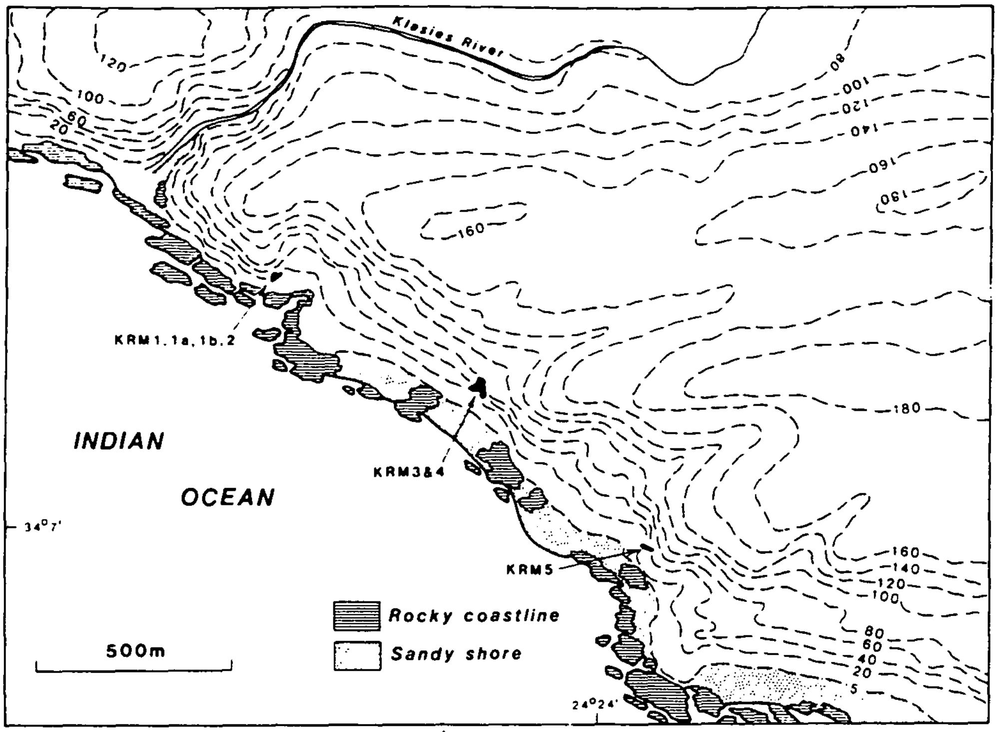

Figure 1 *Location of Klasies River Mouth caves along the southern Cape Coast, South Africa (after Deacon 1985).*

THE NATURE OF ELECTRON SPIN RESONANCE

The potential use of electron spin resonance (ESR) analysis in dating geological materials was first pointed out by Zeller (1968). Little progress was made until the mid-1970s when Ikeya started experimenting with a wide range of geological and biological materials. Summaries of this work can be found in Ikeya (1978, 1985). Ikeya (1978) first hinted at the possibility of dating shells. Early published studies on the dating of marine shells were concerned with bivalves (pelecypods) with predominantly aragonitic shells by Ikeya and Ohmura (1981) and Radke *et al.* (1981). Hütt *et al.* (1983) examined both aragonitic and calcitic bivalves from the northern Soviet Union and the Spitsbergen archipelago. They found that the spectra of the two types were quite different. Calcite spectra were found to have a background of intense Mn^{2+} lines that were not observed in aragonitic species. To the best of our knowledge there are no published papers on ESR analysis of marine gastropods.

ESR dating has close similarities with thermoluminescence (TL) dating. Both are techniques attempting to measure the amount of radiation damage due to ionizing radiation. In ESR spectrometry the presence of defects can be detected because they show characteristic absorption patterns at certain locations within the spectrum. Peaks are produced when the sample is exposed to a fixed microwave frequency in a variable magnetic field. The relative positions of these peaks within the spectrum are identified by their g values. The term 'peak intensity' is used synonymously with 'peak height' since signal width is not dose dependent.

The intensity of the defect signal as seen in the spectrum is compared with an Mn standard and is a measure of the number of defects present in the trap associated with a particular location within the crystal lattice. For a trap to be suitable for absolute dating

Table 1 *Descriptive and analytical details of thirteen shell samples used in study*

Sample No.	*Cave (KRM)*	*Industry*	*Nature**	*Equivalent dose (Gy)* ED_A	ED_B	ED_C	*Uranium (ppm)*	*Potassium (ppm)*
GOE-3	1a	H.P.	c	84	–	59	1.23	160
GOE-4	1a	MSA II	c	91	–	54	1.11	140
GOE-5	1a	MSA II	c	97	–	86	1.17	80
GOE-6	1a	MSA II	c	106	–	69	0.87	85
GOE-7	1	LSA	o	8	–	8	1.00	700
GOE-8	1	MSA II	o	133	49	98	1.48	85
GOE-10	1	MSA I	o	237	102	106	1.24	130
GOE-11	5	LSA	s	10	–	10	0.40	160
GOE-12	5	MSA I	c	412	–	230	1.98	150
GOE-13	5	MSA I	s	302	–	333	2.19	130
GOE-14	5	MSA I	s	414	–	241	0.98	85
GOE-15	1b	MSA I	o	243	61	169	1.14	140
GOE-16	1	MSA I	o	519	–	281	1.54	180

* c. columella; o. operculum; s. shell.

purposes it must have a mean life that is at least an order of magnitude greater than the period of time over which dating is to be carried out (Hennig and Grun 1984). Where this is the case the radiation dose received by a sample is a function of its age. Ideally the dose rate should remain constant over time. The dose consists of two components. The internal dose is due to the presence of radioactive impurities within the sample (mainly uranium, thorium and potassium) while the external dose is derived mainly from radioactive elements in the immediate environment of the sample and to a limited extent from cosmic radiation.

Since any mineral may vary in its sensitivity to ionizing radiation due to the presence of impurities, the measured intensity of the defect signal is not itself a measure of the amount of radiation to which the sample has been exposed. Provided that the intensity of the defect signal has a linear response to radiation doses, the amount of equivalent radiation already received by it can be determined within reasonably precise limits. This amount is known as the equivalent dose (ED) of the sample.

The requirements to be met if ESR analysis is to provide estimates of absolute age can be summarized as follows: (1) radioactive content of the sample must be determined and is assumed to have remained constant during the 'life' of the sample; (2) external dose rate has to be measured *in situ* and has to be assumed to have remained constant over time: (3) the signal used for dating must have a long mean life; (4) the signal must have a linear response to radiation dose over a wide range of values and should be absent from modern samples.

With respect to (1) it will be shown that some of the older samples do appear to have experienced significant uranium enrichment. This makes it highly probable that the immediate environment has also been enriched. It will be shown that the three signals present in the natural spectra have a rather short mean life but that they do have a linear response to radiation dose, even after considerable additional irradiation. Also they are absent from modern samples.

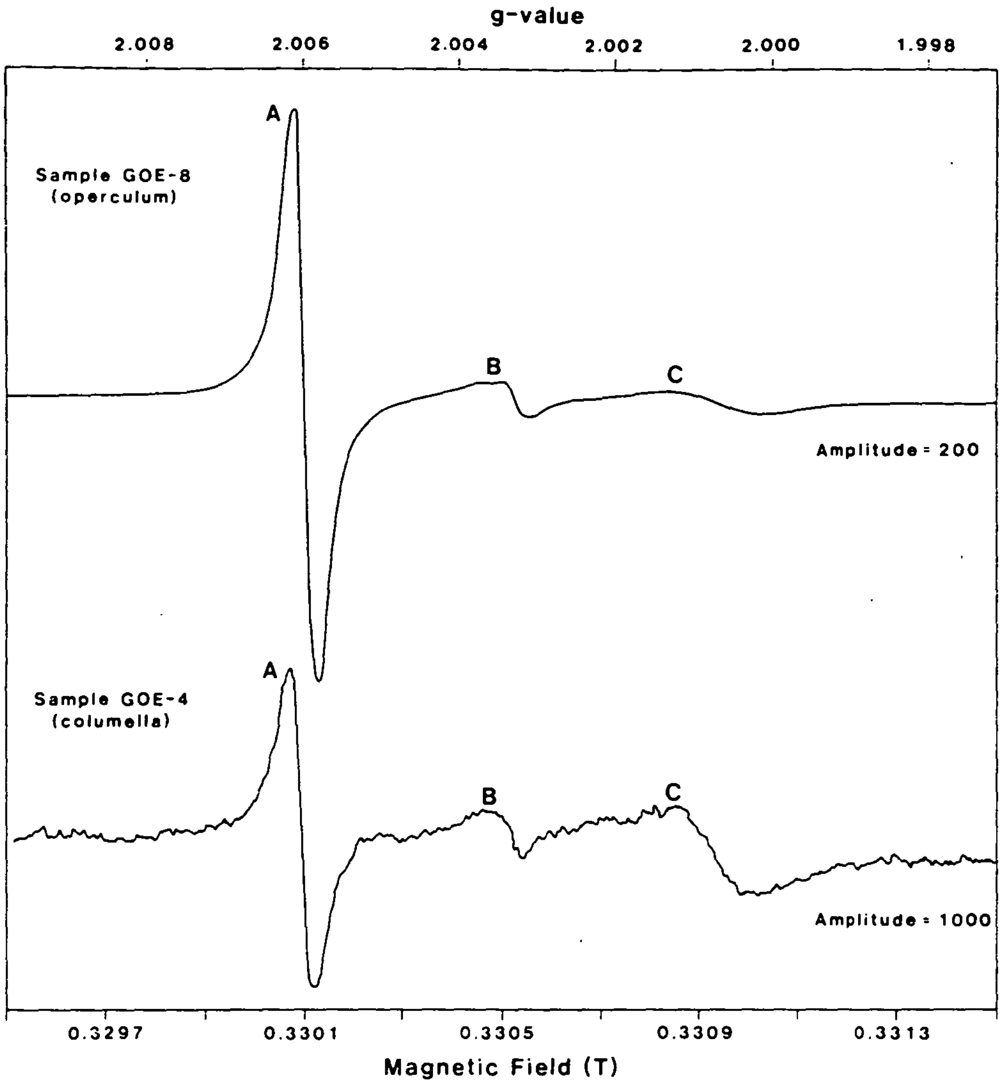

Figure 2 *ESR spectrographs of natural spectra of samples GOE-8 and GOE-4. When comparing the intensity of signal A between the two samples account must be taken of the fact that the spectrum of GOE-4 was run at five times the amplitude of sample GOE-8.*

Clearly the samples are not suitable for absolute age determination. Accumulation of uranium by the shell does not necessarily preclude the use of ESR as a relative dating technique. Provided that accumulation takes place gradually over a long period of time as appears to be the case here it will even extend the time range over which ED values of peaks with relatively short mean lives can be used for relative dating.

SAMPLE PREPARATION

For analysis samples of shell, either columellae or opercula, preferably weighing 10–12 g are etched in 10% acetic acid for up to 1 h. Afterwards they are washed repeatedly in distilled water and allowed to dry at a temperature of < 30 °C. This procedure removes surface shell layers and any adhering detrital contaminants. The samples are then crushed in a swing mill using a hardened chrome steel vessel. Following crushing the size fraction 125–250 μm is

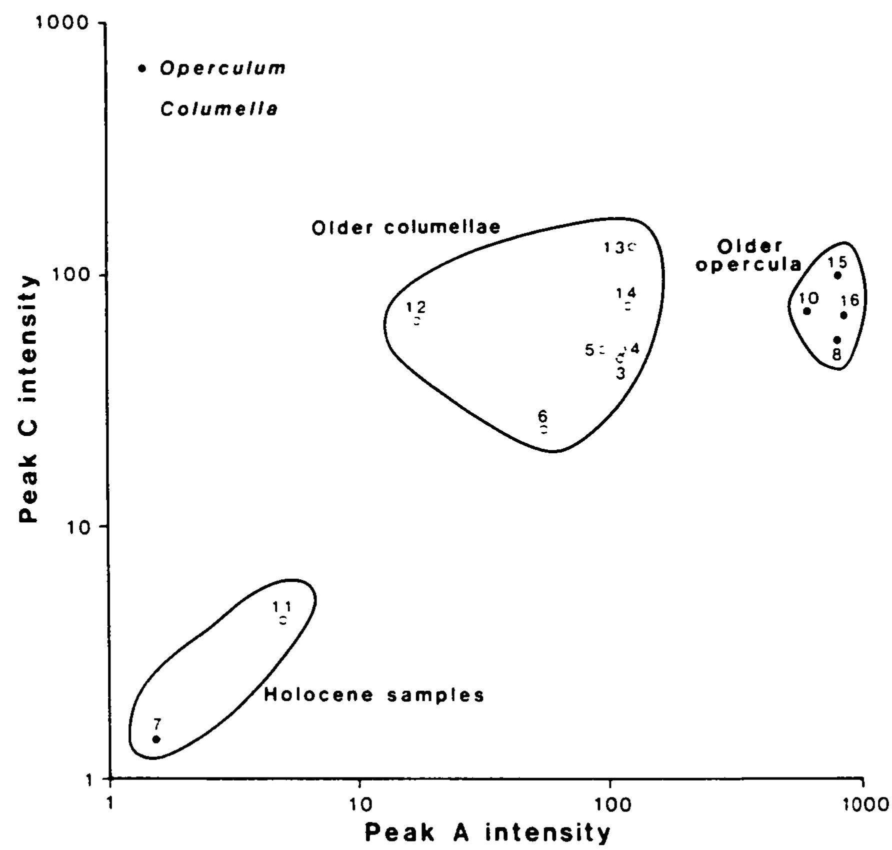

Figure 3 *Plot of peak A* versus *peak C intensities (in arbitrary units). Very weak peak development separates Holocene samples. In older samples peak A intensities are an order of magnitude greater in opercula than in columellae. Peak C intensities are comparable in the two groups.*

separated by sieving. Next this size fraction is washed in 10% acetic acid for several minutes to remove any adhering dust and to etch the grain surfaces lightly. The size fraction is then washed repeatedly in distilled water and allowed to dry as before.

The material is used to provide five sub-samples each approximately 150 mg in weight. One sub-sample is left unirradiated. The other four are exposed to a γ radiation source (Co-60) with length of exposure increasing at approximately equal intervals of time. The irradiation dose rates have been approximately 0.055 Gy/h. The irradiated samples are stored for at least one week prior to measurement to allow fading of unstable ESR signals produced by irradiation. Weighed portions of 100–150 mg of each sub-sample are analysed on a JOEL JES-FE3X ESR spectrometer. Samples were placed in the centre of the cavity under conditions of ambient temperatures at 100 kHz with a magnetic field modulation of 4×10^{-5} T and a microwave power of 5 mW (figure 2).

The spectral peaks are identified using the terminology of Ikeya and Ohmura (1984). Unirradiated samples show only three peaks: A (g = 2.006), B (g = 2.0037) and C (g = 2.0008). In irradiated samples two rather weak additional signals appear: E (g = 2.0022) and D (g = 1.995).

The mineralogy of all thirteen samples used in the analysis was examined using infrared spectrophotometry. It was found without exception that the samples were composed of aragonite. Three samples were heated to 200 C for 30 min without causing any conversion to calcite.

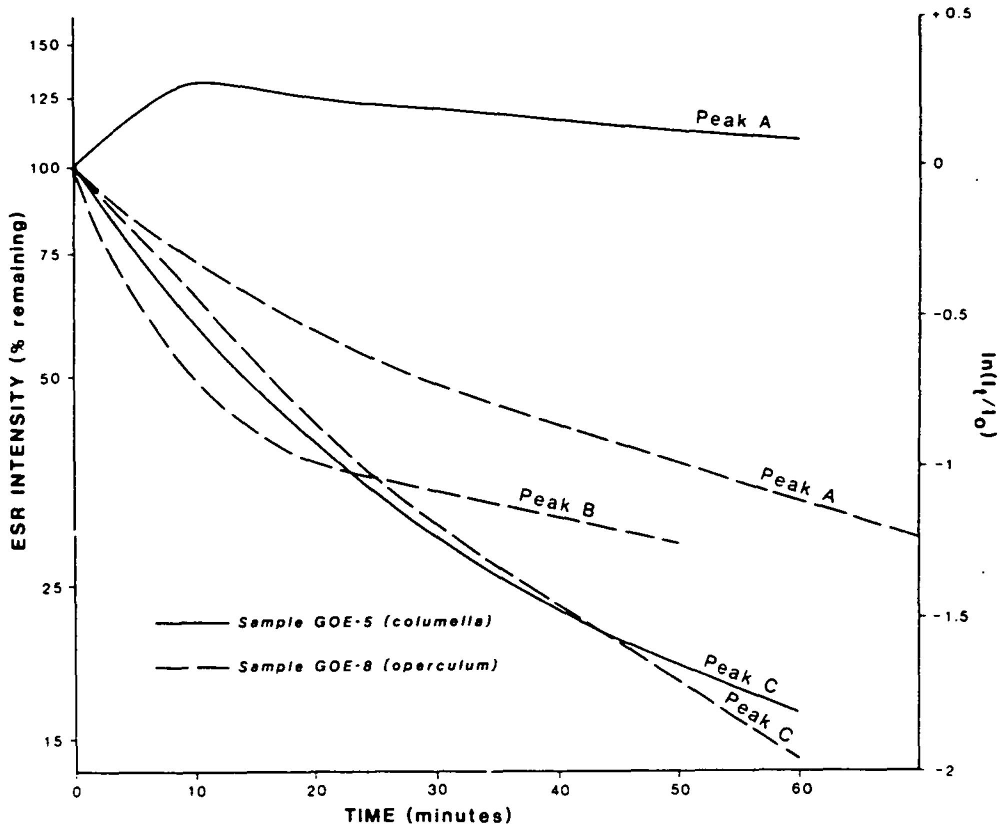

Figure 4 *Decay of peak intensities at 200°C for operculum sample GOE-8 and columella sample GOE-5.*

ANALYSIS

As a preliminary step the spectra of the unirradiated samples were run. In figure 3 the intensities for peak A are plotted against the intensities for peak C. The diagram reveals three distinct groupings. Two Holocene samples (Lower Stone Age (LSA) industry) are characterized by very weakly developed peaks. The older samples all have similar C peak intensities but split into two groups with opercula having a much more intensive A peak than columellae. It is clear that in this species of *Turbo* there is a significant difference in the ESR spectrum between these two parts of the shell. The reason is unknown but may well be related to differences in content of organic radicals or trace element composition (figure 2).

Where sub-samples of each sample are exposed to increments of γ irradiation the intensities of peaks A, B and C all rather surprisingly show a strong positive linear relationship with γ radiation dose. This is in marked contrast with aragonitic bivalves where peaks A and B are frequently either insensitive to irradiation or even decrease in size (Radke 1985).

It is important to determine the mean lives of the electron traps indicated by each of the three peaks in the spectrum. Annealing experiments with natural samples have been used to determine the stability of each signal. Isothermal annealing was carried out at three temperatures (200, 175 and 150 °C) for each of three samples. In figure 4 the decay curves for the three signal intensities is shown at 200 °C for operculum sample GOE-8 and columella sample GOE-5. Ideally the decay curve should be linear when plotted in this

Table 2 *Mean lives in years estimated for the present day mean annual temperature of the site (17 °C)*

Sample No.	*Peak A*	*Peak B*	*Peak C*
GOE-4	–	1.32×10^3	4.50×10^3
GOE-5	–	–	3.09×10^3
GOE-8	1.63×10^4	1.43×10^3	3.69×10^3

manner. However, in the operculum sample all three signals have an initial 'soft' component that decays rather rapidly before a more stable component is revealed. Similar behaviour has been observed by Smith *et al.* (1985) during annealing experiments with calcite speleothems. The effect is particularly pronounced in the case of peak B which initially has the most rapid rate of decay. Peak A is clearly the most stable of the three and therefore appears to be the most suitable for dating purposes. This is again in strong contrast with aragonitic marine bivalves where peak C is usually found to be the only suitable peak.

Annealing of two samples of columellae (GOE-4 and GOE-5) shows quite different behaviour of the A peak (figure 4). Its intensity increased rapidly at first followed by a slow decline but its intensity was greater at the end of the annealing experiment than at the beginning. Similar behaviour of this peak has been observed by Yokoyama *et al.* (1983) in calcite speleothems and has been interpreted as a transfer of spins from other trapping sites including those of peaks B and C. In these two samples peak C shows similar behaviour to that shown in sample GOE-8 while peak B is too weak to be useful in annealing experiments.

For each sample on annealing for each of the three temperatures the mean life of the signal was calculated for each peak showing orderly decay. Calculations were made using the higher values of ln (I_t/I_0) and assuming a linear relationship between this variable and heating time (I_0, peak intensity at time 0; I_t, peak intensity remaining after heating time t). The mean life so calculated should be regarded as a minimum estimate since it emphasises the decay of the 'soft' initial component of the signal. Clearly each signal also contains a component with a significantly longer mean life (figure 4).

Where mean life values are obtained for three different temperatures for a peak the information can be graphed on an Arrhenius plot to estimate the mean life of the signal at any other temperature. The mean lives in years were estimated for the present day mean annual temperature of the site (17 °C) (see table 2).

It is clear that the mean lives of any of the peaks are too short to be useful in absolute dating. Peak A has the longest mean life but it can only be determined in operculum samples. This is followed by peak C while peak B has the shortest mean life of all.

These findings are in conflict with the generalization made by Ikeya (1984) that ESR dating of carbonate fossils, whether calcite or aragonite, should be made using signal C and that the mean life of this signal is sufficiently long for the ESR dating technique to be applicable up to about one million years.

The mean life estimates obtained here are underestimates firstly because they are strongly influenced by the 'soft' components of the signal and secondly because the mean annual temperature of the site has nearly always been significantly lower now than during the Late Pleistocene. These two factors suggest that in reality the signals have a significantly longer mean life at this site. Therefore it was considered worthwhile to continue with the assessment of the value of ESR analysis as a relative dating tool.

RELATIVE AGE DETERMINATION

As described earlier, sub-samples of each sample were exposed to a γ-irradiation source with length of exposure increasing at approximately equal increments. The intensity of each of the signals (A, B and C) was measured for each of the sub-samples. The artificial radiation doses (ARDs) are plotted against the ESR signal intensities and a regression line is calculated. The ED is determined by the intercept of the regression line on the horizontal axis (figure 5).

When a signal has a long mean life relative to the age of the samples, the ED can be regarded as the γ ED of all the radiation the sample has received during its existence. This is not likely to be the case here as it has already been shown that the mean life of all three signals is relatively short. For every sample measured ED values were obtained for peaks A and C. In the case of peak B such values were obtained for only three samples (all opercula). In the other samples the signal was too insensitive to irradiation to determine the ED value with a reasonable degree of precision (table 1).

In general the ED values reflect the relative stability of the peaks as indicated by the annealing experiments. Peak A usually yields higher ED values than peak C which in turn tends to yield higher values than peak B. GOE-13 is an anomalous sample showing a higher ED value for peak C than for peak A. In figure 6 ED values for peak C have been plotted against those for peak A as an EDAC plot. If ED values are useful indicators of relative age we should expect an increase in age from left bottom to top right of the diagram. The industries to which the samples belong have been shown alongside the axes. Group by group the ED_A values are all in the right order. In the case of the ED_C scale the values of GOE-3 and GOE-4 are the reverse of the stratigraphic order but the difference is small and easily accounted for by the limited degree of precision in determining ED values. ED_A values appear to be more useful than ED_C values for relative age determination because of the larger range of values shown and because they can be determined with greater precision because of greater sensitivity to γ radiation.

The samples appear to fall into four groups. Group I clearly represents LSA material of Holocene age. The other groups are much older and there is a suggestion in Groups II and IV that opercula may yield somewhat higher ED values than columellae. This may be related to their different peak A behaviour in annealing experiments. Group II samples all belong to the Howieson's Poort (HP) and MSA II cultural sequence and are closely clustered suggesting a relatively short time period. Groups III and IV are all from the MSA I cultural phase and it is curious that they should fall into two groups. Samples GOE-12, GOE-13 and GOE-14 are all from the KRM5 site while sample GOE-16 is from the basal units of KRM1 (layer 38/39). It is tempting to suggest that they may represent significantly older material.

Another possibility to be considered is that the Group IV samples have been enriched in radioactive elements. Uranium and potassium analyses have been carried out on all samples as well as a number of samples from the present day beach (table 1). Potassium content does not appear to vary much except for an anomalously high concentration of 700 ppm in the Holocene sample GOE-7. Six modern samples yield an average potassium

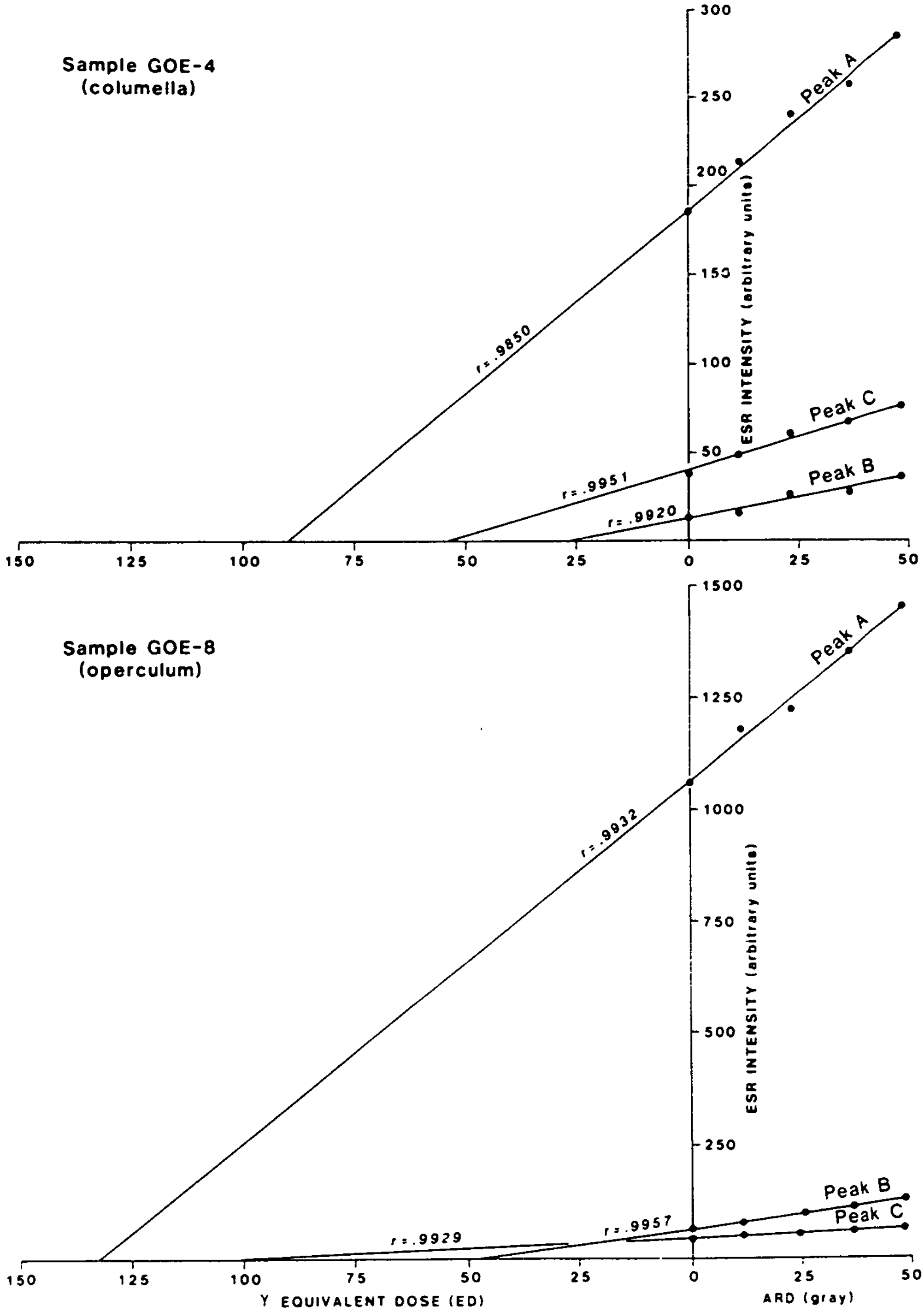

Figure 5 *Use of regression lines of ESR intensity versus artificial radiation dose (ARD) to determine gamma equivalent dose. Note the high sensitivity of the A peak to irradiation.*

content of 143 ± 17.5 ppm. Excluding GOE-7, the remaining fossil samples show an average potassium content of 127 ± 34.9 ppm. There is no significant difference between the two groups.

With uranium twelve modern samples yield an average uranium content of 0.81 ± 0.15 ppm. The average uranium contents of Groups I–IV are respectively 0.70, 1.17,

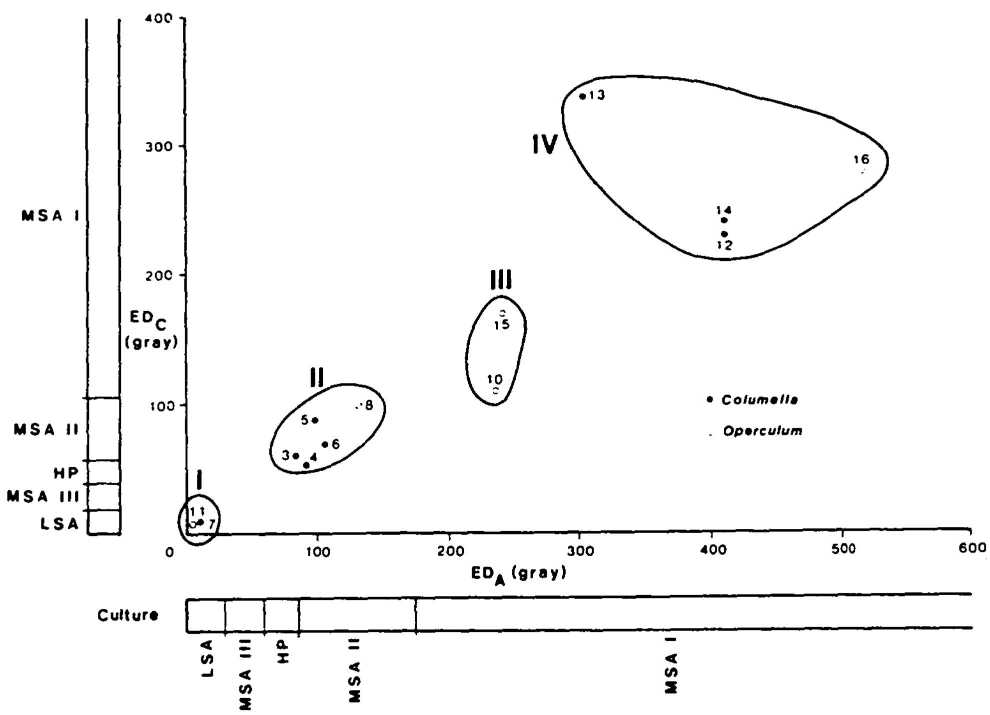

Figure 6 *Equivalent values for peak C plotted against those for peak A. The plot is referred to as an EDAC diagram.*

1.19 and 1.67 ppm. Although nearly all Pleistocene samples appear to have experienced some uranium enrichment the effect is particularly pronounced in the case of Group IV samples. It is probably significant that most of the Group IV samples are close to the base of the stratigraphic sequences in which they occur. This is the most favourable situation for uranium enrichment.

OTHER DATING METHODS

Earlier attempts to determine the age of the deposits using C-14 and aspartic acid racemization dating have been concentrated at sites KRM1 and 1a while C-14 dates only are available for the uppermost part of the KRM5 stratigraphic sequence. A detailed discussion of these attempts is found in Singer and Wymer (1982). All deposits older than LSA appear to be >40 000 B.P.

Four aspartic acid dates on bone were determined by Bada and Deems (1975) for the lower part of the KRM1 sequence. The age estimates range from 65 000 B.P. for layer 13 to 110 000 B.P. for layer 38. This makes sample GOE-8 approximately 80 000 B.P. and GOE-10 significantly older than 110 000 B.P.

A project of ionium dating of speleothem materials from KRM1 and 1c is being undertaken by J. C. Vogel of the CSIR, Pretoria. Initial unpublished results (Vogel pers. comm.) are consistent with the aspartic acid dates in suggesting the base of the KRM1 sequence, layer 38 (MSA I) from which GOE-16 was collected, is older than 100 000 years (Deacon *et al.* 1986) and that samples from layers 17 (MSA II) upwards in KRM1 are somewhat younger. Samples dating the oldest period of stalagmite formation, which preceded the deposition of the basal grits overlying clast supported beach materials on bedrock in the back of KRM1, have still to be processed. The age of the beach at the base of the sequence is unknown but predates the Last Interglacial (Hendey and Volman 1986).

Oxygen isotope analyses of shell by Shackleton (in Singer and Wymer 1982) have shown that the only pre-Holocene shells with an O-18 isotopic composition as light as the LSA (Holocene) shells indicating fully interglacial conditions are those associated with layers yielding MSA I artifacts. The age of these shells is correlated with isotope stage 5e which elsewhere has been dated to approximately 125 000 B.P. (Kaufman 1986) or even 140 000 B.P. (Chappell 1983). The exception is KRM1b where the oxygen isotope values deviate significantly from those for the equivalent culture stratigraphic horizons in KRM1 and 5 and the Holocene.

It is possible to suggest that the shell samples placed in group IV on the basis of their ED values represent deposits related to an earlier interglacial. In that case they have to date back at least to isotope stage 7 between 190 000 and 230 000 B.P. (Chappell 1983), as Shackleton (Singer and Wymer 1982) has already shown that the KRM5 Pleistocene shell deposits were laid down under full interglacial conditions. If such an age can be confirmed by either ionium or aspartic acid dating it would indicate a much earlier beginning of the MSA in South Africa than is generally accepted although Wendorf *et al.* (1975) refer to K/Ar dates from East Africa hinting at a possible beginning date for MSA of more than 180 000 B.P. The suggestion that the MSA I deposits in KRM5 and basal MSA I deposits in KRM1 date back to an older interglacial appears to be unlikely on present evidence. It is much more probable that the high ED values of Group IV samples are due to the degree of uranium enrichment although this does not explain the high values for sample GOE-14.

CONCLUSIONS

ESR analysis of *Turbo sarmaticus* shells collected from Holocene and Pleistocene midden deposits at Klasies River Mouth has shown that opercula and columellae have significantly different spectra. The short mean lives of the defect sites represented by signals A, B and C render them unsuitable for absolute dating. Nevertheless ED values obtained from peaks A and C appear to provide suitable indicators of relative age when plotted in the form of an EDAC diagram (figure 6).

In future applications of ESR dating to *Turbo sarmaticus* analysis should be restricted to opercula that show no significant uranium enrichment (uranium content < 1 ppm). If these conditions are adhered to, the technique should provide a rapid and reasonably reliable method of relative age determination. It can be used either to determine relative ages of different sites in the same area or to estimate the time depth of a shell accumulation at a single site.

Of particular interest is sample GOE-15 from KRM1. This is located a little lower stratigraphically than the mandible of *Homo sapiens* recorded from layer 9. The sample's ED value places it firmly in Group III and therefore in the MSA I culture. This agrees with the temporal correlation proposed by Singer and Wymer (1982) who regarded the deposits in KRM1b as contemporary with beds 37 to 40 in KRM1. It does not support the contention of Binford (1984) who regards the deposit as younger and places it either in late MSA II times or even after Howieson's Poort.

The fact that all three MSA I samples from KRM5 fall into Group IV raises the interesting possibility that these deposits may be older than the Last Interglacial.

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ELECTRON SPIN RESONANCE (ESR) ANALYSIS - RECENT DEVELOPMENTS AND AGE DETERMINATION OF MARINE SHELL

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ABSTRACT

A review is presented of some recent developments in the dating of teeth, bone and shell. It is argued that there are a number of obstacles to the accurate estimation of numerical ages. Archaeologists should be less obsessed with numerical dating since there are considerable advantages in relative dating as an alternative strategy. Examples are drawn from South Africa, Western Victoria and Tasmania. Relative dating is particularly appropriate where multiple techniques can be applied to date depositional events that recur at discrete time intervals.

INTRODUCTION

ESR, like its cousins thermoluminescence (TL) and optical dating (OD), is a method of age determination belonging to a rapidly developing group of radiogenic dating methods that measure radiation damage and energy storage due to radioactive decay in biologically and chemically deposited materials. They can also be applied to the dating of sediments exposed to light during the depositional process, as long as suitable minerals are present containing radiation induced signals that can be at least partially bleached by exposure to sunlight. OD is restricted to sediment dating and is still in an early stage of development but already shows considerable promise for the dating of certain types of sediment (Berger, 1986; Godfrey-Smith and Huntley, 1987).

The three methods differ in the way in which radiogenic effects are measured. In OD only the concentration of light sensitive electron traps is measured using luminescence induced by an argon ion laser. In sediment dating OD could have a significant advantage over the other two methods. In TL the samples are heated through a range of temperatures up to 500^0 C and the intensity of the emitted light is measured. ESR analysis requires measurement of the strength of defects by exposing the sample to a

fixed microwave frequency in a variable magnetic field. This produces a spectrum with one or more characteristic peaks that are identified by their g-values. Some of these relate to radiation induced defects and are sometimes suitable for dating.
ESR has some advantages over TL. It can be applied to a wider range of materials since heating involved in TL analysis may change the nature of materials such as bone, aragonite and gypsum. TL samples can be analyzed only once since the radiogenic defects are destroyed in the analytical process. This is not the case with ESR where the sample may be analyzed repeatedly. A disadvantage of ESR is that the measurement of defects is less sensitive than in TL. In normal environments it cannot be used to estimate ages of less than 2ka.

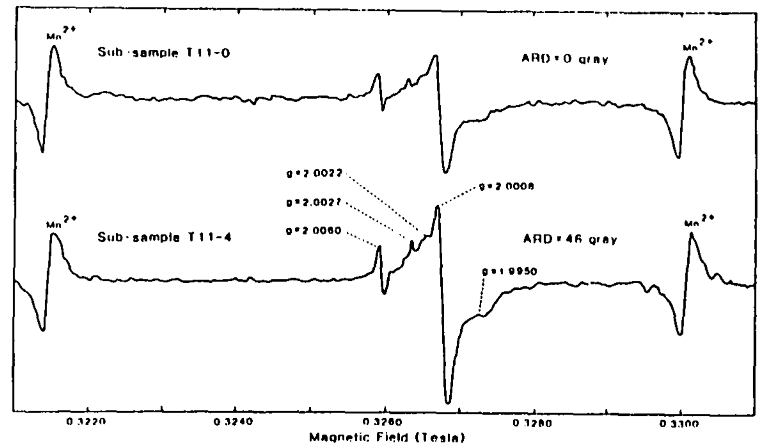

Figure 1. ESR spectra of Tasmanian Pleistocene shell sample of *Glycymeris (Tucetilla) striatularis*. Sub-sample T11-0 shows the natural spectrum while T11-4 has been exposed to an artificial radiation dose (ARD) of 46 gray. The peak used for analysis is at g=2.0008 and the effect of the ARD is clearly seen. The Mn^{2+} peaks are not part of the sample's spectrum but are due to the presence of a manganese marker.

ESR samples are prepared by crushing followed by sieving to isolate a selected fraction, usually 125-250 µm. Grains are then etched and/or washed to provide clean surfaces for optimum analytical conditions. After drying, the sample is subdivided into a number of sub-samples, usually five or more. One sub-sample is left unirradiated while the others are exposed for stepped increments of time to a gamma-radiation source to give a range of artificial radiation doses (ARDs). Each sub-sample is than analyzed in an ESR spectrometer that scans through a range of magnetic field intensities to produce a spectrum (Fig. 1). A spectral peak suitable for dating should have a long mean life and should be sensitive to gamma-radiation with peak intensities preferably showing a linear relationship with ARD. Extrapolation of the regression line fitted to the points can be used to estimate the gamma-equivalent dose (ED) (Fig. 2). Where similar sites are being compared ED values can be used for relative age determination. For numerical dating the annual dose rate has to be determined. If this is assumed to have remained constant during the "life" of the sample then

Age = ED / annual dose rate

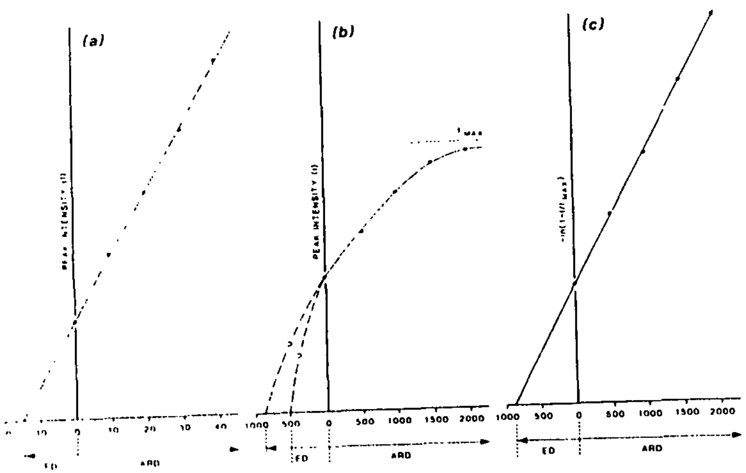

Figure 2. (a) Relationship between peak intensity (I) and artifical radiation dose (ARD) for five sub-samples. A regression line is fitted and extrapolated to the horizontal axis to estimate the γ-equivalent dose (ED) - an estimate of the radiation dose the sample has received since the death of the animal.

(b) For adequate analysis of old samples large ARDs are required and the relationship may become non-linear due to saturation effects.
(c) To obtain estimates for old samples, peak intensity (I) is replaced on the vertical scale by a logarithmic expression that involves the value of I at saturation (I_{max}). The resulting linear relationship allows more reliable extrapolation to estimate the ED value.

RECENT ADVANCES IN ESR

Many recent advances in ESR have already been outlined in the Second Australian Archaeometry Conference by Ikeya (1987) and in the case of bone by Caddie et al (1987). Apart from the possibility of dating sediments ESR is of most interest to archaeologists because it offers a possibility of dating bone, teeth and aragonitic shell.

Recent work by Grün, Schwarcz and Zymela (1987) has shown that tooth enamel is an excellent material for ESR analysis using the hydroxyapatite peak at g=2.0018 to obtain ages up to at least 1-2 Ma with a precision of 20%. However, a number of problems remain to be solved before the method can be regarded as giving even reasonably accurate numerical age estimates.

Grün and Schwarcz (1987) have recently published a critique of ESR dating of bone and make a comparison with tooth enamel. ESR analysis of bone uses the same signal (g=2.0018) for dating but, unlike tooth enamel, bone in living animals has a high organic content and the inorganic portion is predominantly amorphous. The process of fossilization begins soon after death and involves crystallization, dehydration, decomposition of chemical constituents and chemical replacement. Many of these major diagenetic changes are poorly understood. The ESR spectrum of bone may contain intense signals due to the presence of amino-acids or other organic compounds containing free radicals. These signals may interfere with the g=2.0018 signal used for dating.

Dating of tooth enamel, bone and shell is complicated by the fact that they do not remain closed systems with respect to uranium. Numerical dating requires a model of uranium uptake. Two different accumulation models may be used. Early uranium uptake (EU) assumes that the uranium content accumulated soon after burial while linear uranium uptake (LU) proposes continuous uptake of uranium approximated as a linear function of time (Grün and Schwarcz, 1987). Since there is frequently no evidence as to which model is the appropriate one to use, two ages may be calculated - one for each model. While tooth enamel is much less likely to experience significant uranium enrichment than either bone or dentine it is often found in close contact with them and this complicates external dose rate calculations.

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Grün and Schwarcz (1987) concluded that "Given the complexity of diagenetic processes affecting fossil bone (including the complexity of its U-uptake history), it is, in our opinion, impossible at this time to perform ESR dating on bones". While this statement refers to numerical dating it does not necessarily apply to relative dating where many assumptions required for the calculation of a numerical date can be relaxed. The potential of bone for relative dating has also been stressed by Caddie et al (1987).

Following the pioneering work on aragonitic shell of Ikeya and Ohmura (1984) and Grün (1985) several workers in Europe and Japan are now producing numerical dates (Radke et al, 1985; Katzenburger and Grün, 1985) and Hütt et al, 1985). Attempts to date calcitic shells have not met with much success because ESR spectra of calcitic shells are strongly affected by the presence of intense Mn^{2+} lines that interfere with the peak normally used for dating (g=2.0008). Ninagawa et al (1985) claim to have made progress towards solving the problem but when this author applied their procedure to the oyster species *Ostrea angasi* abnormally low ED values were obtained for a specimen of Last Interglacial age. Experiments on several other species of calcitic shells are still in progress.

IS NUMERICAL DATING JUSTIFIED?

Numerical dating of aragonite shell is now carried out by a number of researchers and at least in some cases reasonable agreement has been obtained with other dating methods.The most consistently reliable method for comparison is $^{230}Th / ^{234}U$ dating of corals associated with shell deposits (Ikeya and Ohmura, 1983). However, most ESR studies of shell have been carried out in temperate environments where corals are rare or absent. Serious doubts remain about some of the assumptions made to obtain numerical dates although aragonite shell is a much better material for analysis than bone as diagenetic changes after death are far less significant.

It is known that fossil shells, composed originally of aragonite, can change their mineral composition to calcite. In older sedimentary rocks this has frequently happened, but there are few if any authenticated cases of this happening to shells in Quaternary deposits except where shells have been heated to high temperatures at midden sites. Changes in mineralogy can be easily detected using either X-ray diffraction of infrared spectrophotometry techniques. Other problems relating to reliable numerical dating of shell are as follows:

(1) Mean life of signal used for dating. For a signal to be suitable for numerical dating

the mean life should be an order of magnitude greater than the time range over which numerical dating is applied. The mean lives obtained can be extrapolated to lower temperatures using an Arrhenius plot (Hennig and Grün, 1984; Grün 1985). The signal at g=2.0008 used to date aragonite shell also occurs in calcite. For speleothem calcites mean lives of 7.3 and 2.5×10^6 years at 15°C have been reported by Hennig and Grün (1984). For the same material Smith et al (1985) observed a mean life of 7×10^7 years at 10°C but also observed that some samples had a less stable component that decayed more rapidly. Ikeya (1984) has claimed that since the signal in both calcite and aragonite is essentially of the same origin, comparable mean lives can be expected. The little experimental data available does not support this contention. Radke in Hennig and Grün (1984) quotes mean lives for mollusc species of 2.5×10^5 and 4.4×10^5 years at 10°C - much lower values than those obtained for speleothem calcite. However, the authors do not make it clear that the material is aragonite. Goede and Hitchman (1987) carried out annealing experiments on three samples of a marine gastropod from South Africa and found that the peaks contained a less stable component with a mean life of between 3.1×10^3 and 4.5×10^3 years at 17 °C. This suggests that the signal at g=2.0008 may not be suitable for numerical dating in aragonite shell although more work on a range of species in required.

(2) Uranium uptake history. Shells are open systems with respect to uranium although they do not normally reach the extreme levels of U-enrichment that may be encountered in bone. Kaufman et al (1971) have published analytical data for a large number of Pleistocene molluscs - mostly from North American sites. The highest recorded U content is 32 ppm and many shells have concentrations in excess of 1 ppm. Personal experience based on fossil shell samples from South Africa, Western Victoria and Tasmania suggest that in these areas U contents in excess of 2 ppm are uncommon and many shells have less than 1 ppm.

Schwarcz (1982) suggests a EU model for uranium accumulation in shell but no evidence is presented to substantiate this claim. Goede and Hitchman (1987) provide evidence that marine gastropods from coastal midden sites accumulate U gradually over a long period of time. In this case at least a LU model for uranium uptake would be more appropriate.

In numerical dating the uptake model adopted can make a considerable difference to the age estimate especially if the uranium content of the shell is high. With a low U content it is less significant because the accumulated dose is largely due to the external dose received by the sample.

(3) Alpha efficiency factor (k-factor). While β particles and γ radiation are nearly 100 % efficient in producing defects the same is not true of α particles where only a small part of the energy is used in this way. When calculating the contribution of α particles to dose rate it is necessary to take the k-factor into account. It has been claimed by Hennig and Grün (1984) that k-factors for calcite show large variations ($k = 0.1$ to 0.6) and this may also be the case for aragonite. When dating Pleistocene aragonite shells Ikeya and Ohmura (1984) adopted a value of $k = 0.2$ but there is no concensus on the most appropriate value to be used.

(4) Temporal changes in sample sensitivity to gamma irradiation. Both Katzenburger and Grün (1985) and Goede (in prep.) found strong correlations between calculated ED values and sensitivity to gamma irradiation. The available evidence suggests that it is an age related variable. It could result in significant overestimation of ED values in older shells.

Considering the problems involved in numerical dating, some of which may not be satisfactorily resolved, it appears that numerical dating cannot provide dates of acceptable accuracy.

RELATIVE DATING - AN ACCEPTABLE ALTERNATIVE?

An individual ESR date of molluscs tends to be judged against the results produced by other numerical dating methods, some of them equally unreliable, e.g., aspartic acid dating (Bada and Deems, 1975) and ^{230}Th / ^{234}U dating (Kaufman et al, 1971). The alternative to numerical ESR dating is the determination of ED values for the purpose of relative dating. Because many of the requirements for numerical dating can be relaxed, a relatively large number of analyses can be produced at low cost. The analyses can then be examined in terms of age related groupings. The use of relative dating techniques in Quaternary studies has grown rapidly in recent years and an excellent summary of a range of such methods is given by Brookes (1982). A well known example is the study of weathering rind thicknesses of buried clasts especially in glacial deposits, but there are many others.

Murray-Wallace and Kimber (1987) have recently evaluated amino-acid racemization as a relative dating technique and applied it to marine sediments in South Australia. This work has now been extended to sites in other states (Murray-Wallace et al., 1988). Goede and Hitchman (1987) have used ESR analysis of shell as a relative dating technique on coastal archaeological sites in Southern Africa. It was evident from this study that for best results the analyses should be restricted to shells with a U content of

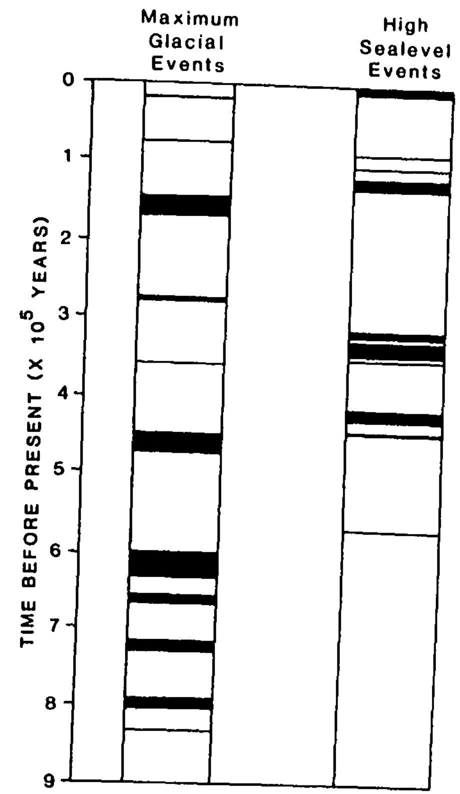

Figure 3. Time spectra for high sealevel events and maximum glacial events based on the oxygen isotope ratio of planktonic foraminifera of deep sea core V28-238 (Shackleton and Opdyke, 1973). Variations in the ratio predominantly reflect volume changes in the oceans. High sealevel events are based on ratios within 10% of Holocene values while maximum glacial events are based on isotopic ratios within 10% of the Last Glacial Maximum. For simplicity the time scale is based on the assumption of a constant sedimentation rate and the age of the Brunhes - Matuyama polarity reversal. Quaternary stratigraphy has recently been dated much more accurately by the application of orbital tuning (Martinson et al., 1987).

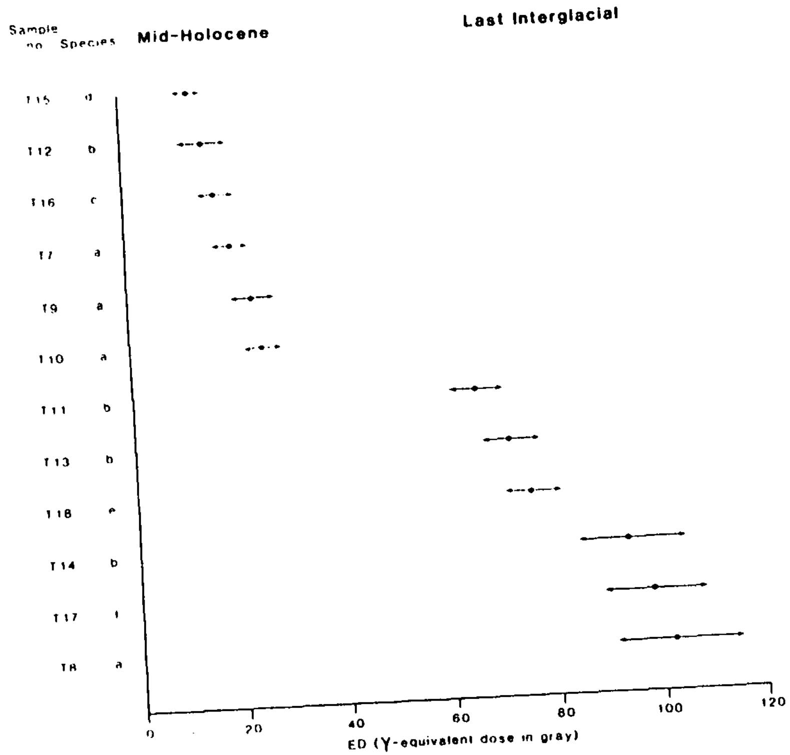

Figure 4. Equivalent dose determinations of twelve Tasmanian shell samples selected from mid-Holocene sites as well as sites judged to be Last Interglacial from detailed chronostratigraphic studies. Samples represent six different species from seven sites. Despite diversity of species, there is clear separation of the two age groups. Species are as follows: a-*Fulvia tenuicostata*, b-*Glycymeris (Tucetilla) striatularia*, c-*Katelysia rhytiphora*, d-*Katelysia scalarina*, e-*Paphies (Atactodea) erycinaea*, f-*Phacosoma coerulea*.

less than 1 ppm. Goede (in prep.) has applied the same technique to Quaternary sediments in the Warrnambool area. The investigations followed a report to the media by the late Mr Edmund Gill of the discovery of two aboriginal midden sites that he believed to be of Last Interglacial age - Hopkins Estuary and Point Ritchie. ESR analyses showed that the two sites were not of the same age. While the Point Ritchie site is of Last Interglacial age the Hopkins Estuary site appears to be considerably older. This has since been confirmed by other dating methods (Gill et al. in prep.).

Relative dating is particularly effective where a number of techniques can be applied to a series of deposits. Under these conditions multivariate statistical analysis can be employed to group sample sites objectively into meaningful relative age categories (Dowdeswell and Morris, 1983).

Relative dating techniques are especially well suited to the dating of depositional events that recur at discrete time intervals separated by significant periods of non-deposition. Examples relevant to Australia are glacial deposits laid down during glacial maxima and marine sediments deposited during interglacial high sea-levels (Fig. 3). Other examples are speleothem deposition in caves in mid-latitudes under interglacial conditions and the deposition of cave entrance breccias produced by frost weathering under glacial climatic conditions. In many middle latitude regions deposition of loess could be added to the list.

WORK IN PROGRESS

The writer and Colin Murray-Wallace, of the N. W. G. MacIntosh Centre for Quaternary Dating at the University of Sydney, are engaged in a joint relative dating project of Quaternary shell sites in Tasmania. Both ESR analysis and amino-acid racemization techniques are being applied. Figure 4 shows the results of ESR analysis of twelve Tasmanian marine shell samples collected from a number of sites. Two distinct age related groups of ED values are apparent.

POTENTIAL FOR AUSTRALIAN ARCHAEOLOGY

ESR analysis is a rapid and inexpensive method for the relative dating of similar sites that contain any one or more of shell, teeth and bone. It can be applied to both coastal and inland sites and may be combined with amino-acid racemization techniques and other relative dating methods to produce age groupings prior to going to the expense of quantitative dating techniques. These methods may be the only ones that can be used when sites are beyond the range of radiocarbon dating.

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NEW DEVELOPMENTS IN LUMINESCENCE DATING TECHNIQUES

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ABSTRACT

The last three years have seen steady progress in the development of thermoluminescence techniques for dating a variety of materials and the introduction of the potentially versatile new technique of photoluminescence dating. In the research area there have been many advances in our understanding of how TL mechanisms operate, with particularly fruitful contributions from the spectral analysis of various phosphors and the systematic study of the bleaching efficiency of sunlight. New instruments have been developed to increase the speed and accuracy of dose rate measurements. The introduction of γ-spectrometry for detailed analysis of radionuclides is helping to resolve problems of disequilibrium in the uranium and thorium series. It is now possible to date a variety of materials previously thought to be undatable. Several examples of the successful dating of sediments of known ages up to 200,000 years are generating confidence in the future of TL and PL in geological applications.

INTRODUCTION

Although the thermoluminescence (TL) dating technique may now be regarded as routine by some hopeful archaeologists, the truth is that each new archaeological site or geological formation is a challenge to their scientific colleagues, and often generates a preliminary research project before the "routine" dating methods can be applied. This research may lead to new methods of dating. Perhaps the most outstanding example is the birth of photoluminescence* (PL) dating as a result of studies by Huntley in Vancouver, Canada, on the sunlight bleaching of TL from sediments. PL dating is in its infancy but is already being researched in several laboratories around the world, while TL dating continues to develop into new areas and to stimulate new research into fundamental mechanisms. The variety of this work was obvious at the Specialist Seminar on TL and ESR in Cambridge in 1987, as a selection of the most significant contributions will show. This review describes the current state of TL and PL dating and also provides a summary of the literature (not intended to be comprehensive) which has appeared since the Second Australian Archaeometry Conference in 1985. The presentation of the material attempts to illustrate how the various avenues of research, prompted by dating experience, provide feedback to dating methods (Figure 1).

*The terms "optically stimulated luminescence" and "optical dating" are also used but we suggest "photoluminescence" and "PL dating" as being more consistent with the terms used for TL dating. See "Current papers in physics", INSPEC Publication, classifications 78.55 and 78.60.

STALAGMITES AS MONITORS OF ENVIRONMENTAL CHANGE

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ABSTRACT

For some time stalagmites have been used as information systems for palaeotemperature. Isotopic studies of the $^{18}O/^{16}O$ ratio of speleothem calcite and the D/H ratio of fluid inclusions have shown that, where deposition has taken place under conditions of isotopic equilibrium, they can be used as sources of palaeotemperature information.

Other potential information sources in speleothems have largely been neglected so far. For example, the carbon isotope ratio $^{13}C/^{12}C$ is shown to vary significantly in some stalagmites and may be an indicator of changing surface vegetation patterns.

ESR analysis has been applied as a means of dating speleothems but it will be shown that the technique can also be used to detect variations in trace element composition that may reflect environmental change.

INTRODUCTION

Recent years have seen an explosion of high quality palaeoenvironmental information from ice cores taken through the Greenland and Antarctic ice sheets. Measurements of D/H (Jouzel et al., 1987) and $^{18}O/^{16}O$ ratios (Lorius et al., 1985; Dansgaard et al., 1982) have been used to reconstruct palaeotemperatures for up to 160 ka B.P. Analysis of trapped air bubbles in the ice has led to the unexpected discovery that atmospheric CO_2 content has varied dramatically during glacial - interglacial cycles and this has led to the re-assessment of the mechanisms of global climatic change (Barnola et al., 1987).

The measurement of ^{10}Be concentrations in Antarctic ice and their strong correlation with the ^{18}O curve suggests that this cosmogenically produced impurity can be used to assess variations in the rate of ice accumulation (Raisbeck et al., 1987). These authors also suggest that unusually high peaks of ^{10}Be may be due to periods of low magnetic field strength, possibly associated with geomagnetic excursions. The micro-particle and chemical stratigraphies of some ice cores have also been examined and can provide information on volcanic eruptions (Hammer et al., 1987), seasonal layering (Wilson and Hendy, 1981) and dust levels (Miklishanskiy et al., 1980). This paper will examine some possibilities of obtaining similar information from uniform diameter stalagmites.

UNIFORM DIAMETER STALAGMITES

Such stalagmites often grow continuously over time periods of tens of thousands of years and form a series of cuspate layers that are usually gently convex upward in shape. When dated by means of multiple ^{14}C or $^{230}Th/^{234}U$ dates it is commonly found that long term growth is linear (Goede and Harmon, 1983). When dates are plotted against height above base, a linear regression line can be fitted to the plot and the regression equation used to estimate the age at any point above the base of the stalagmite. Five dated uniform diameter stalagmites are available from the Mole Creek karst area in Northern Tasmania (Fig. 1) and two of these form the basis for this study (Goede and Harmon, 1983; Goede and Hitchman, 1983). Details of two stalagmites formed under conditions of isotope equilibrium and their palaeo-temperature curves have been published (Goede and Hitchman, 1983; Goede, Green and Harmon, 1986).

Stalagmites have some advantages over cores of glacial ice as palaeoenvironmental information storage systems. Unlike glacial ice, speleothem deposits are not subject to increasing overburden pressures that lead to progressive deformation and thinning. Also, unlike ice, storage of speleothem samples does not require special environmental conditions. A third advantage is that speleothems give information on changes in local conditions while the records obtained from glacial ice relate specifically to high latitudes. Most Tasmanian uniform diameter stalagmites appear to have grown at rates of 2-5 cm/ka but some at least grow much more rapidly up to

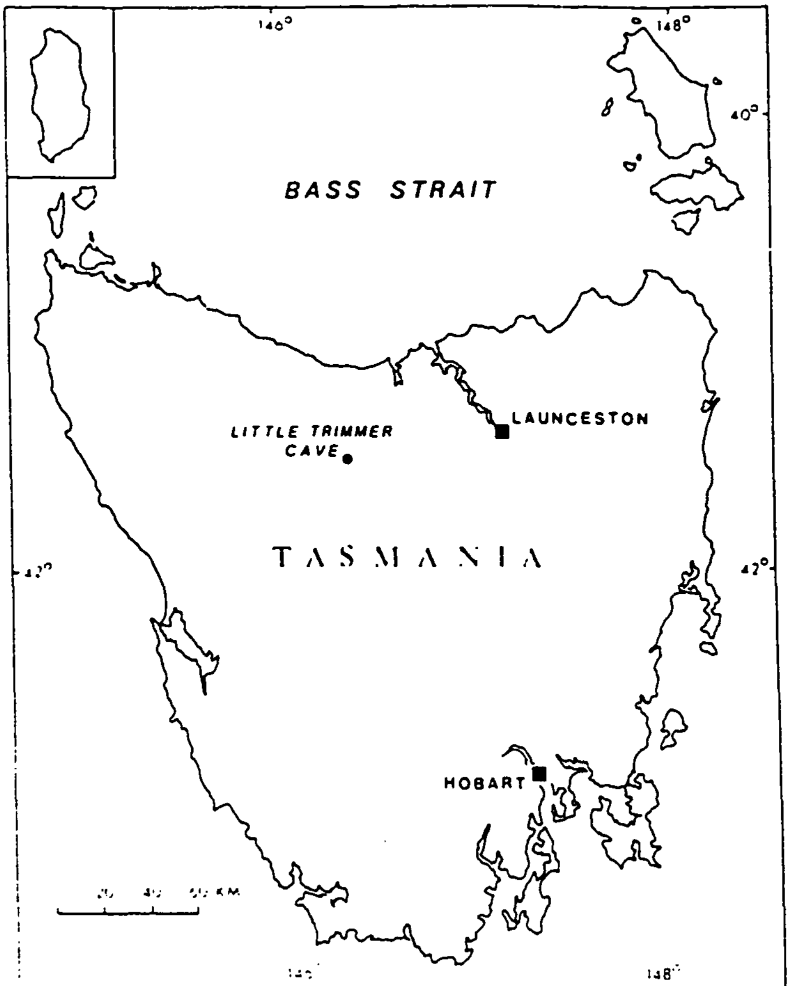

Figure 1 *Location of Little Trimmer Cave site.*

60 cm/ka. This means that sampling can take place at close time intervals.

A disadvantage of stalagmites is, that unlike ice, they do not form annual layers and the presence of short hiati in the record may be difficult to detect. The greatest problem is that atmospheric information is filtered by the passage of water through vegetation, soil and bedrock. However, vegetation and soil may impart additional information to the system.

When calcite is deposited from seepage water, further modification of the information content may occur. For example, if deposition occurs under conditions that encourage evaporation, fractionation will take place and the calcite will be enriched in the heavier isotopes of the oxygen and carbon pairs. Such fractionation can be detected by selecting a single growth layer and drilling out a number of samples, usually seven, from the centre outwards. Isotopic analysis of these samples will show a consistent trend towards isotopically heavier values if fractionation has occurred. It is assumed that trace element composition could also be affected by evaporation.

ELECTRON SPIN RESONANCE (ESR) ANALYSIS

ESR is usually employed as a dating method for speleothem calcite. The method was pioneered by Ikeya (1975) but considerable progress has been made since. A good example of its recent application to speleothems is given by Smith, Smart and Symons (1985).

ESR spectrometry detects defects in the crystal structure that are due to the presence of free electrons and free radicals. Defects are recognized through the presence of characteristic energy absorption peaks in a spectrum obtained by exposing the sample to a fixed microwave frequency in a variable magnetic field. Spectral peaks are identified by their g-values. Un-irradiated calcites from cave sites at Mole Creek usually show two peaks at g=2.006 and g=2.0008, sometimes referred to as h_1 and h_3 respectively (Smith et al., 1985). Signal h_1 is usually weak in pure calcites and unsuitable for dating (Fig. 2).

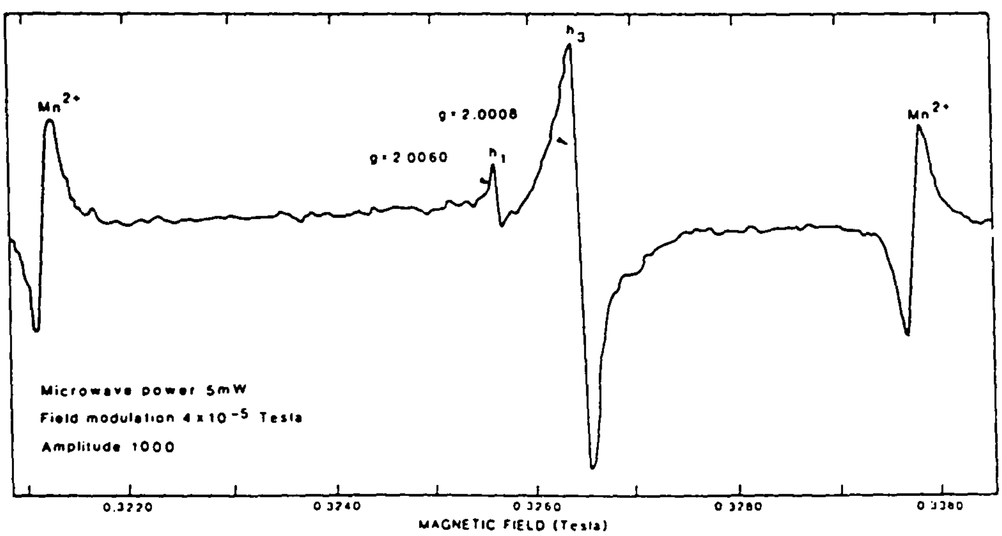

Figure 2 *ESR spectrum of calcite sample from core of LT Stalagmite showing h_1 and h_3 peaks. The Mn^{2+} peaks are not part of the sample's spectrum but are due to the presence of a manganese marker.*

Signal h_3 is suitable for age determination as it shows a strong linear response in intensity to gamma irradiation over a wide range of values. Annealing experiments have shown that it has a sufficiently long mean life to permit quantitative age determination up to 0.8-1.0 Ma (Henning and Grün, 1983; Ikeya, 1984).

Age determination requires an estimate of the gamma-equivalent dose (ED) of the sample, usually expressed in grays. Samples are prepared by taking 5-10 gm of calcite and crushing it in a swing mill. The size fraction 125-250 microns is separated by sieving. The grains are etched in 10% acetic acid to remove surface defects that may cause interference with peak h_3 in the ESR spectrum. Samples are then washed repeatedly in distilled water and dried in a cool oven. The size fraction is sub-divided into five sub-samples each weighing some 150 mg. One sub-sample is kept in the natural state but the other four are exposed to regular increments of gamma radiation from a ^{60}Co source. This artificial radiation dose (ARD) is measured in grays.

The sub-samples are individually analysed on an ESR spectrometer. For each, the h_3 peak intensity is measured a number of times and an average value taken. The h_3 peak intensities, expressed in arbitrary units are then plotted against the corresponding ARD (Fig. 3). The points usually form a linear plot and a regression line is fitted. The ED value of the sample is determined as the distance between the point of origin and the intersection point of the regression line and horizontal axis. The slope of the regression line (a) is a measure of the sensitivity of the sample to gamma irradiation, provided that peak intensity is always measured in the same units. The age of a sample can be determined, once the ED value is known, as long as the annual irradiation dose (ID) can also be estimated. The age is calculated by

$$\text{Age} = ED/ID$$

The brief discussion of ESR as a dating method has been necessary in order to understand the concepts involved. However, in this paper, the method is used for a rapid assessment of changes in trace element composition along the growth axis of a stalagmite since both the nature of the spectrum and sensitivity of peaks to gamma irradiation may reflect such changes.

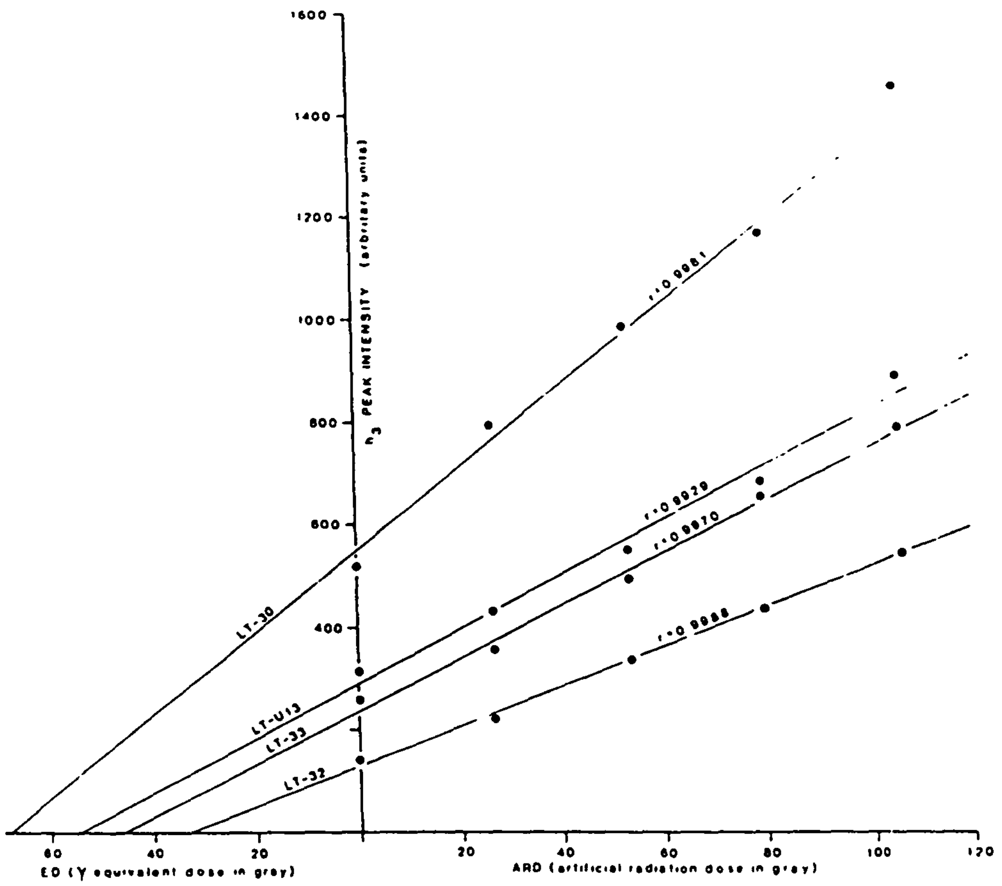

Figure 3 *Intensity of peak h_3 plotted against ARD for four samples in order to determine their ED values and gamma ray sensitivities.*

For this purpose the stalagmite is cut longitudinally and small samples (150 mg weight) are drilled out at close intervals along the long axis with a slowly rotating masonry drill. Without any further preparation the samples are analysed in the ESR spectrometer. Such untreated samples give a slightly decreased signal strength but in many other respects produce satisfactory spectra that can be readily compared. The advantage of small samples is that it allows temporal changes in trace impurities in calcite to be studied in detail as only ten minutes are required to analyse each sample.

A comparison of spectra not only detects changes in the intensity of the h_3 peak but will also detect the presence of other peaks and changes in their intensities. For example, the presence of Mn^{2+} produces a very characteristic spectrum consisting of a sextet of hyperfine lines with a doublet of minor peaks between each pair. Several organic radicals (e.g. methyl and alanine) also give rise to highly characteristic patterns of hyperfine lines (Robins, 1988).

Until now, ESR analysis of speleothems has not been used in this way, but such an approach has been applied to other materials. Van Moort and Russell (1987) used ESR spectra to distinguish between auriferous and barren vein quartz as some impurities associated with gold mineralization produce characteristic defects in quartz. Similarly, Robins (1988) has used ESR spectra to study jet jewellery from the European Bronze Age and has been able to differentiate jets from similar organic materials.

ANALYSIS OF STALAGMITES

Two uniform diameter stalagmites (LT and LX) from Little Trimmer Cave, Mole Creek (Longitude 146°14'41", latitude 41°34'21") have been the subject of detailed study. The LT stalagmite was 142 cm tall and on the basis of seven $^{230}Th/^{234}U$ dates was found to have grown between 108 and 76 ka BP at a rate of 4.3 cm/ka. Except for the basal 35 cm, it had been deposited under conditions of oxygen isotope equilibrium. A palaeotemperature curve for this speleothem has been published together with full details of the $^{230}Th/^{234}U$ dates. The $^{230}Th/^{232}Th$ activity ratios of the dated samples indicate that the level of detrital contamination is quite low (Goede, Green and Harmon, 1986).

The LX stalagmite was 55 cm tall and on the basis of three $^{230}Th/^{234}U$ dates was found to have been deposited between 95 and 69 ka BP growing at a rate of 2.1 cm/ka (Goede and Harmon, 1983). Tests showed that it has not been deposited under conditions of oxygen isotope equilibrium so that $^{18}O/^{16}O$ ratios could not be used to construct a palaeotemperature curve. Once again the $^{230}Th/^{232}Th$ activity ratios of the dated samples indicated a low level of detrital contamination.

The same samples from the LT stalagmite that had been used to determine $\delta^{18}O$ and $\delta^{13}C$ values were also examined for their ESR spectra. It was found that the h_3 peak, normally used for dating, showed striking variations in intensity. When peak intensity values (Ih_3) were plotted alongside the isotopic curves, there was found to be a close correlation between them and the $\delta^{13}C$ values (Fig. 4). This was a totally unexpected discovery. Correlation, regression analysis was carried out on 36 pairs of values and yielded a correlation coefficient of r=0.8001 explaining almost two thirds of the variance. Student's t test (d.f.=34, t=7.7773) indicates a level of

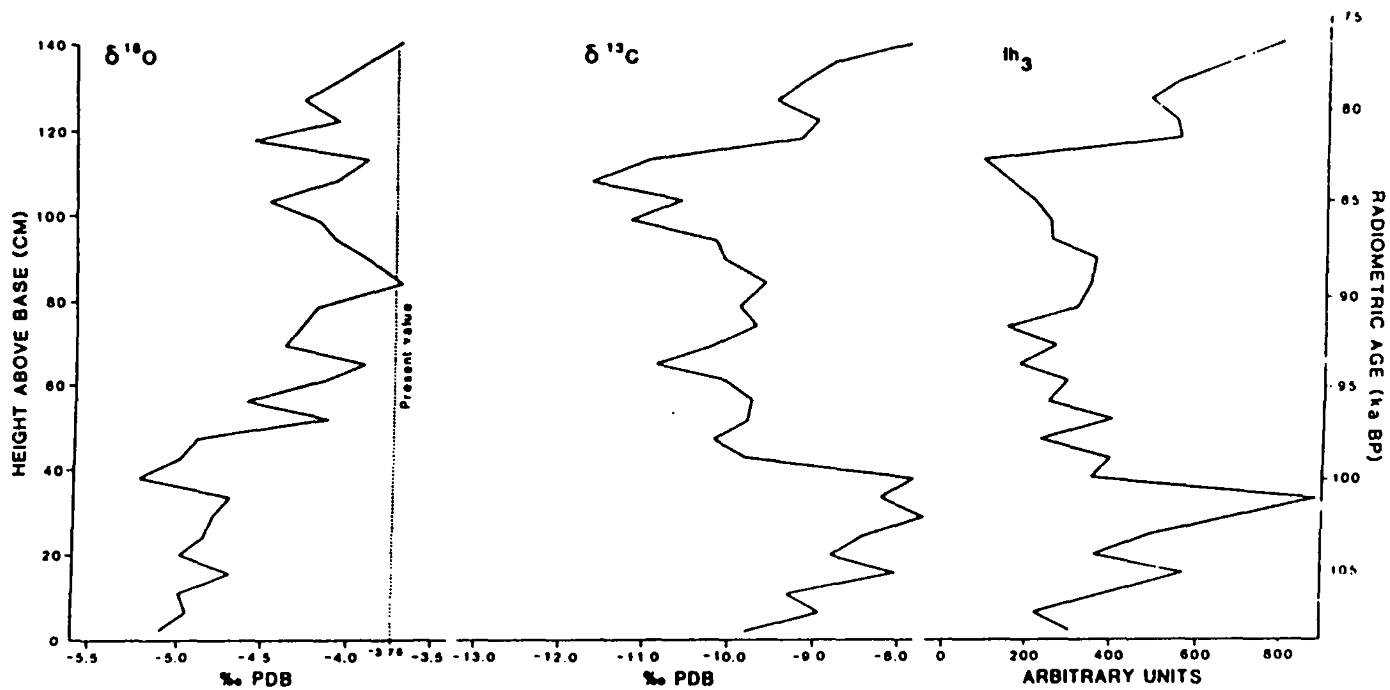

Figure 4 *Comparison of profiles of $\delta^{18}O$, $\delta^{13}C$ and Ih3 values in the LT stalagmite. Close similarities are observed in the profiles for $\delta^{13}C$ and Ih3.*

significance <<.001. The correlation is clearly highly significant. In LX a similar situation is found (Fig. 5). A comparison of 55 values of $\delta^{13}C$ and Ih_3 gives a highly significant correlation (r=0.8209, d.f.=53, t=10.4650).

At this stage it is necessary to investigate the possible reasons for the variations in $\delta^{13}C$ values and Ih_3 values in the two stalagmites. Variations in the $\delta^{13}C$-content of speleothem calcite were first reported by Galimov and Grinenko (1965) who recognized the role played by vegetation in providing soil CO_2 depleted in $\delta^{13}C$ and its involvement in the solution process. Studies by Thompson et al. (1976) and Talma et al. (1974) have also tentatively attributed variations in speleothem $\delta^{13}C$ values to vegetation change. It is well known that groups of plants with different biochemical pathways (C_3, C_4 and CAM metabolisms) have different fractionation effects (Smith and Epstein, 1976). The marked variations in $\delta^{13}C$ could be interpreted as reflecting oscillations between a moist climate associated with forest vegetation rich in C_3 type plants and a drier, possibly colder, climate associated with grassy vegetation dominated by C_4 type plants. Interpretation must remain speculative, especially as little is known about the metabolisms of Tasmanian plant species.

It has been pointed out by Hendy (1970) that the $^{13}C/^{12}C$ ratio of speleothem calcite may also depend on the extent of isotopic exchange between carbon dioxide in the cave atmosphere and the carbon dioxide in solution leading to a progressive enrichment in the heavier isotope as carbon dioxide is lost from the bicarbonate saturated solution.

Variations in the intensity of the h_3 peak in the ESR spectrum may also reflect more than one cause. Peak intensity is a function of age, sensitivity to gamma radiation (Sg) and uranium concentration (U). If age were a significant factor one would expect a trend towards lower values with increasing height above the stalagmite base. Goede and Hitchman (1983) found an example of this when they examined a much younger stalagmite from Lynds Cave, Mole Creek. In older stalagmites, such as LT and LX, differences due to age tend to become insignificant compared with other sources of variation. In fact no age related trend is apparent in either of the two profiles (Figs. 4 and 5).

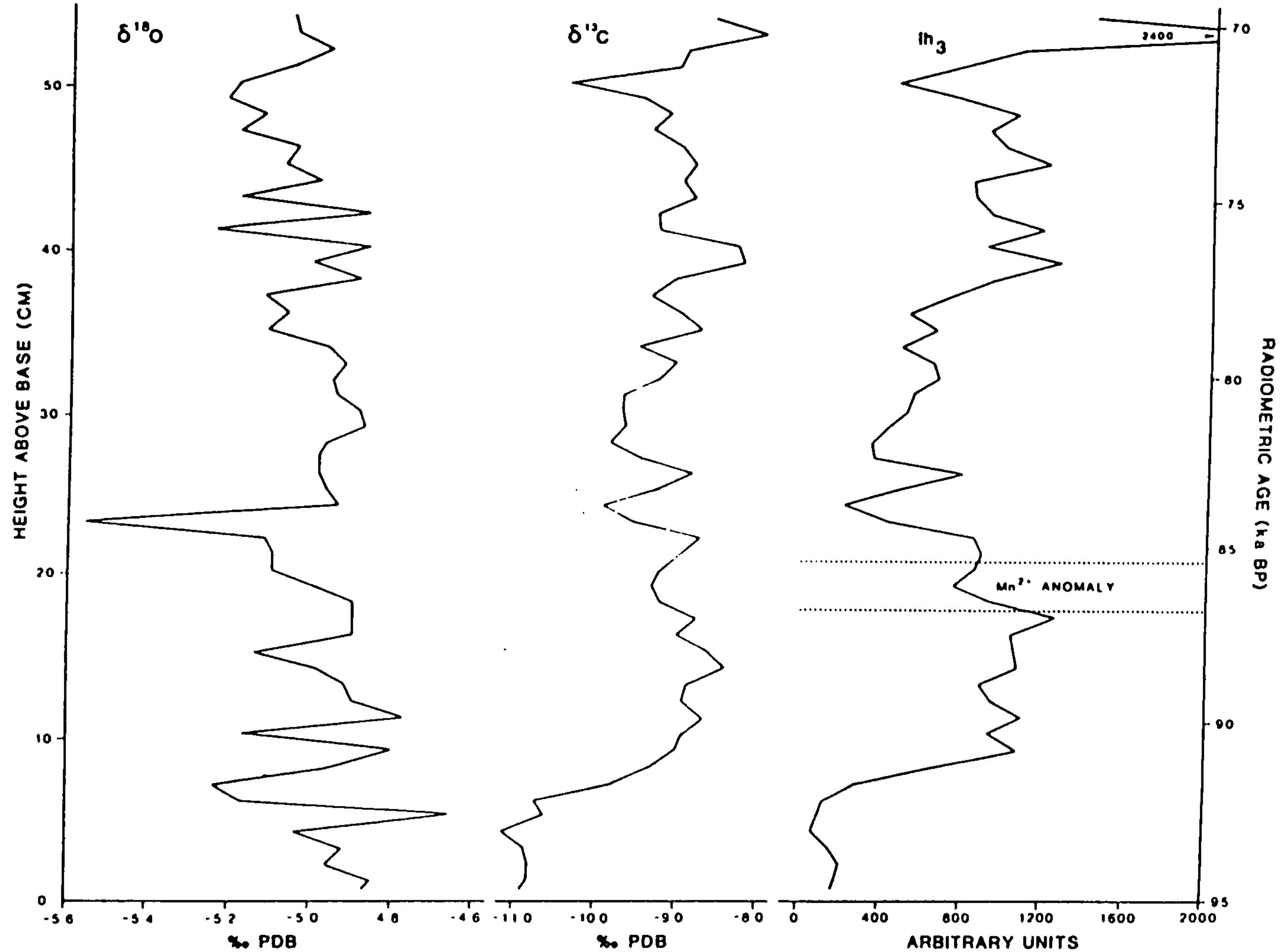

Figure 5 *Comparison of profiles of $\delta^{18}O$, $\delta^{13}C$ and Ih3 values in the LX stalagmite.*

To test the influence of sensitivity to gamma radiation (Sg) on values of Ih_3, eight portions of the LT stalagmite were selected with Ih_3 values ranging from 166 to 2846 (arbitrary units). At these positions 5 mm thick slices were cut from the core and crushed. The samples were then treated as discussed earlier for ESR age determination and each was divided into five subsamples subjected to incremental doses of gamma irradiation. The Sg value was then determined for each sample. Values varied by a factor of two compared with a, factor of seventeen for Ih_3 values. Other things being equal, a doubling of the Sg value of a sample should double the Ih_3 value. It appears that only a small proportion of the variation in Ih_3 is explained by variations in Sg. This is confirmed by correlation regression analysis which yielded $r=0.4292$, d.f.=6, $t=1.1640$. The correlation is not statistically significant.

It remains to examine variations in the uranium content (U) in the two stalagmites. Determination of U (in p.p.m.) for fifteen samples from LT with corresponding Ih_3 values gave $r=0.8642$, d.f.=13, $t=6.1928$. The regression equation is:

$$Ih_3 = 3398U - 2504 \quad (1)$$

Similarly, determination of U (in p.p.m.) for twelve samples from LX with corresponding Ih_3 values gave $r=0.7358$, d.f.=10, $t=3.4360$. The correlation is again statistically significant and the regression equation is

$$Ih_3 = 2862U - 1023 \quad (2)$$

Equations (1) and. (2) cannot be explained as simple cause and effect relationships because even with no uranium content (U=0), Ih_3 should still have a positive value due to growth induced by external gamma radiation from the immediate environment of the sample. A possible explanation is that the growth of the h_3 peak in the ESR spectrum is inhibited by a trace impurity whose concentration has an inverse relationship to the uranium content.

In both stalagmites there are also significant correlations between $\delta^{13}C$ values and uranium content. For LT, correlation regression analysis yields $r=0.8424$, d.f.=13, $t=5.6366$. When the analysis is repeated for LX we obtain $r=0.7253$, d.f.=10, $t=3.3317$.

Another phenomenon observed in the ESR spectra of three consecutive samples in the profile of the LX stalagmite is the presence of six hyperfine lines, with a doublet of minor peaks between each pair. It indicates the presence of Mn^{2+}. Although this pattern is frequently seen in ESR spectra of limestone samples, it is normally absent from speleothem calcite.

CONCLUSIONS

The fact that close correlations have been established independently in two stalagmites between values of $\delta^{13}C$, uranium content and h_3 peak intensity in ESR spectra indicates that these relationships have wider significance. The covariance between the three variables may be related to vegetation change if the suggestion is accepted that the large observed variations in $\delta^{13}C$ are predominantly due to shifting dominance in vegetation elements with different metabolic pathways.

However, when $\delta^{13}C$ variations in the two stalagmites are compared over the same time period there appears to be little similarity in the two curves (Fig. 6). If vegetation change is the dominant control on these variations, the lack of correspondence between the two curves may reflect the well known fact that cave drips draw their water supply from a very localized area. What we see may be the effect of individual trees rather than regional changes in vegetation.

The presence of significant amounts of Mn^{2+} in three samples from the LX stalagmite may reflect the occurrence of waterlogged soil conditions at the surface. The timing of the event giving rise to the presence of Mn^{2+} occurs within the growth period of the LT stalagmite but no Mn^{2+} was found to be present in any of its samples. This may indicate that the manganese anomaly in the LX stalagmite represents a very localized phenomenon rather than a regional change in soil drainage conditions due to a change in climate.

It appears that further studies of the temporal variations in both inorganic and organic impurities, as well as the isotopic ratios $^{18}O/^{16}O$, $^{13}C/^{12}C$, and their relationships to variations in ESR spectra would be very worthwhile. Once a characteristic of the ESR

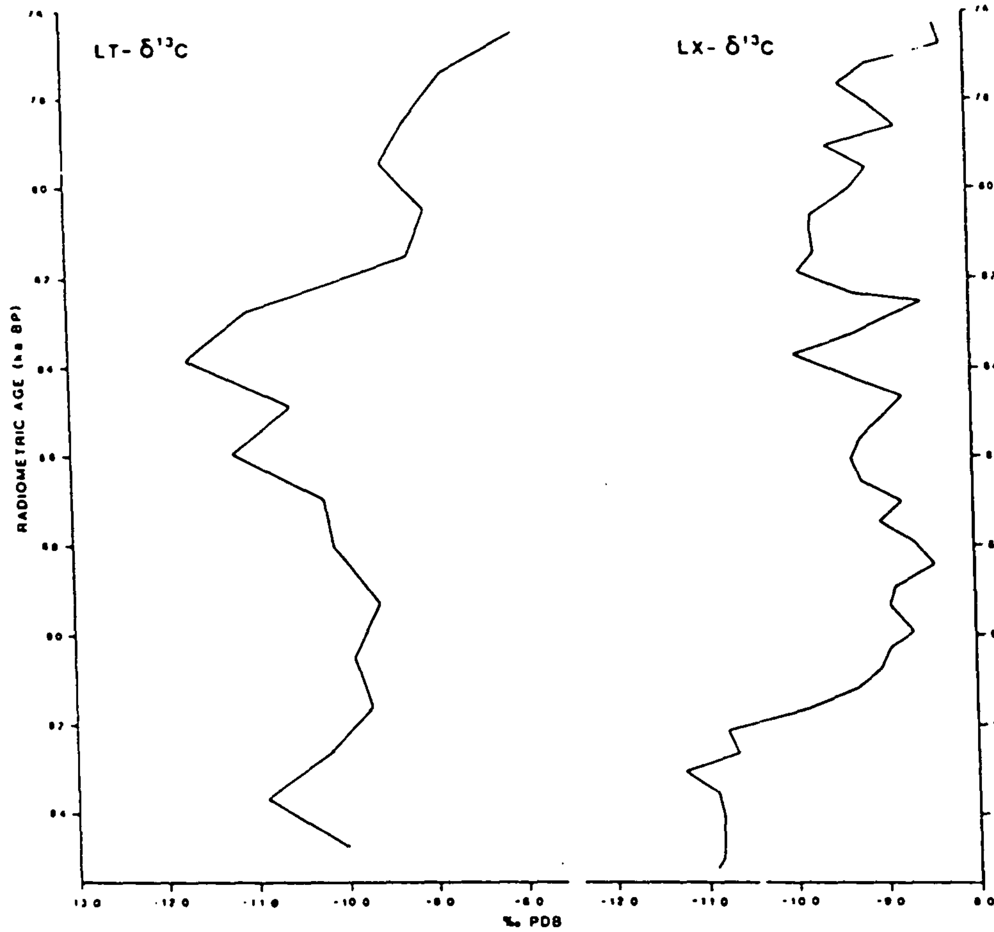

Figure 6 *Comparison of $\delta^{13}C$ variations in LT and LX stalagmites over the time span during which both were growing simultaneously. Little similarity is evident.*

spectrum is linked to a chemical impurity or stable isotope ratio, ESR analysis can be used to provide extremely detailed profiles that, particularly in the faster growing stalagmites, can be used to study in detail the occurrence and development of short term events such as abrupt climatic changes of short duration.

ACKNOWLEDGEMENTS

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18

Electron Spin Resonance—A Relative Dating Technique for Quaternary Sediments Near Warrnambool, Victoria

A. GOEDE

An assessment is made of the application of electron spin resonance (ESR) analysis of aragonitic molluscs for chronostratigraphic studies of Late Quaternary marine and estuarine sediments in western Victoria. Evaluation of the gamma equivalent dose (ED) provides a measure of the amount of natural radiation a mollusc has received since its death. In the absence of significant uranium enrichment the ED values of samples collected from similar sedimentary environments provide a reliable measure of relative age. The use of 95% confidence limits of ED values enables the discrimination of distinct age groups of molluscs. The age groups are referred to here as ED zones. One coastal marine species, the gastropod Turbo (Subninella) undulatus *shows a time dependent change in sensitivity to gamma radiation that can also be used to discriminate between ED zones. ESR analysis can be used in combination with amino acid racemization studies to correlate Quaternary coastal deposits in southern Australia.*

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INTRODUCTION

The author's involvement in this study stems from the release of a report to the media in May 1986 by the late Mr E. D. Gill of Melbourne. Mr Gill announced the discovery of two Aboriginal shell midden sites, which he believed to be of Last Interglacial age, near Warrnambool in western Victoria. ^{14}C analyses at both sites, Hopkins Estuary and Point Ritchie, had shown the age of the shell to be at or beyond the range of the dating method. The announcement led to a number of researchers becoming involved in the interpretation and dating of the two sites. It has now been shown beyond reasonable doubt that the Hopkins Estuary site is not a midden site although it has some unusual features (Gill *et al.*, in prep.). The Point Ritchie site is still under investigation (Prescott and Sherwood, 1988). The author's

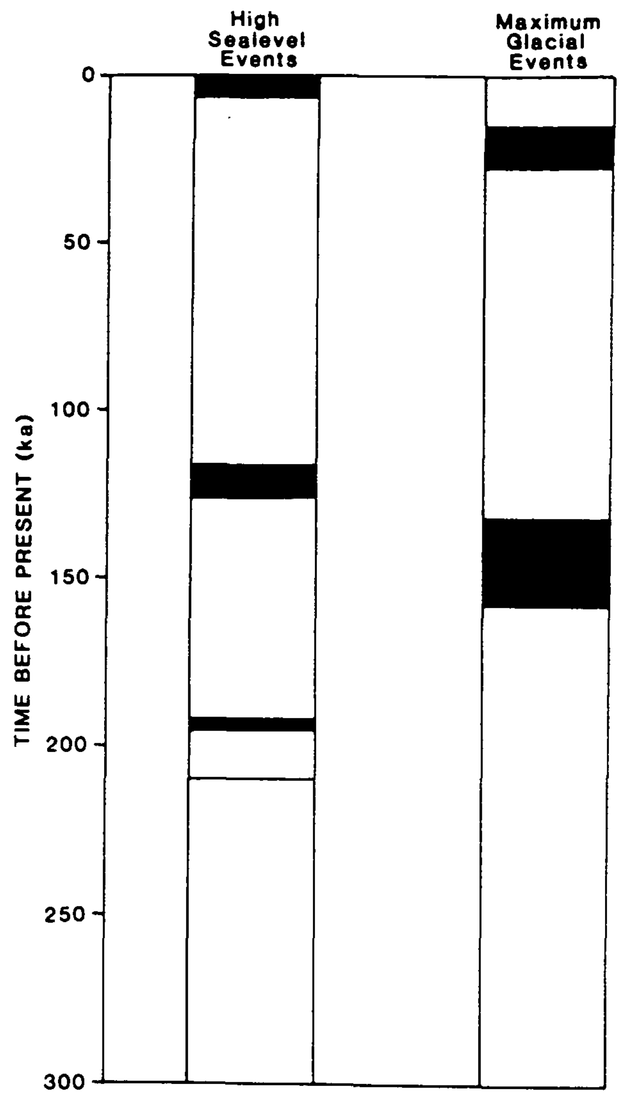

Fig. 1 Time spectra for high sealevel events and maximum glacial events based on the oxygen isotope ratio of planktonic foraminifera in deep sea core RC11-120 (Martinson *et al.*, 1987). Variations in the ratio predominantly reflect volume changes in the oceans. Maximum glacial events are based on isotopic ratios within 20% of the Last Glacial Maximum while high sealevel events are based on ratios within 20% of Holocene values.

contribution to the project was the application of electron spin resonance (ESR) analysis to fossil shells to test whether the sites were of Last Interglacial age.

Relative dating techniques lend themselves particularly well to dating depositional events that occur at discrete time intervals separated by relatively long periods of non-deposition. Good examples of deposits resulting from such events are glacial sediments laid down during Quaternary glacial maxima or marine deposits associated with interglacial high sealevels. Time spectra for deposits of this sort can be derived from $^{18}O/^{16}O$ profiles obtained from deep sea cores (Fig. 1). However, it must be firmly kept in mind that not every event in

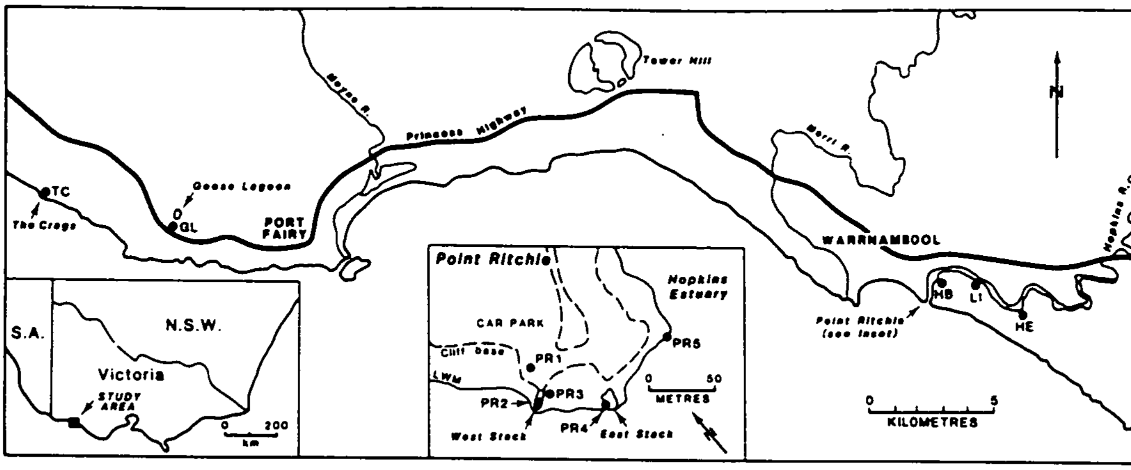

Fig. 2 Locality map of the study area with sample sites shown.

the spectrum is necessarily represented by sedimentary evidence as sediments deposited during a particular event may have been removed by subsequent erosion or may not have been detected during fieldwork. The application of relative dating techniques to deposits of this nature yields groups of samples of particular relative age which may be correlated with the relevant part of the dated $^{18}O/^{16}O$ spectrum. However, in order to apply this method properly, it is necessary to sample a large number of sites in an area. In the case of the Warrnambool area, many sites are known as a result of detailed fieldwork by Gill and Sherwood (pers. comm.), but with two exceptions (Gill, 1977) details have not been published. Most of the additional sites represent deposition by natural processes, while two are Holocene Aboriginal middens. As time in the field was limited it was not possible to make detailed stratigraphic observations at each site. Site localities are shown in Fig. 2 and grid references are given based on the 1:100,000 Warrnambool and Mortlake topographic sheets.

A number of successful applications of relative dating techniques within Australia have been made, especially in Tasmania. Bowden (Bowden and Colhoun, 1984) used the degree of surface solution of siliceous sponge spicules from shallow marine sediments in northeastern Tasmania to help support the division of these sediments into a number of chronozones. Kiernan (1983) used the thickness of weathering rinds of dolerite clasts in glacial and glaciofluvial deposits in western Tasmania to distinguish three glacial stages. Augustinus and Colhoun (1986) used variations in specific gravity and percentage absorption of water of Cambrian volcanic clasts to show the presence of glacial deposits of three different ages in another area of western Tasmania.

Murray-Wallace and Kimber (1987) have evaluated amino-acid racemization as a relative dating technique for Quaternary marine sediments in South Australia. Provided that all samples are taken from similar sedimentary environments in a restricted geographic area and as long as only species with similar racemization behaviour are grouped, then the method can be used successfully to define aminozones, chronozones based on the racemization technique.

ESR has been used as a technique of relative dating in Australia by Hewgill *et al.* (1983) who applied it to a number of emergent marine units in Western Australia. They were able to distinguish Holocene and Last Interglacial material from older units. However, they did not place confidence limits on their equivalent dose (ED) values and obtained an unusually high ED value for a Holocene sample. Goede (1988) has advanced reasons why ESR dating of shell should be used as a relative rather than a numerical dating method.

NATURE OF ELECTRON SPIN RESONANCE

ESR dating has similarities with the better known technique of thermoluminescence (TL) dating in that both attempt to measure quantitatively the amount of radiation damage in a sample due to the effects of ionizing radiation. In TL dating, samples are heated through a range of temperatures and the light given off at each temperature is measured. The resultant spectrum shows various peaks that can be related to critical temperatures at which different types of traps, features that store ionized particles within the crystalline lattice of the sample, become unstable. The method has the disadvantage that information contained in the sample is destroyed in the process of measurement. Also some materials, such as gypsum and aragonite shell, may change their chemistry and/or mineralogy during the heating process. This generates non-radiation induced TL which interferes with the spectral peaks used for dating. These materials are suitable for ESR analysis because no heating of the samples is involved.

ESR spectrometry detects the presence of defects through the characteristic absorption patterns in a spectrum produced by exposing the sample to a fixed microwave frequency in a variable magnetic field. The spectral peaks are identified by their g-values and also, in the case of aragonite shell, by an alphabetical code using the terminology of Ikeya and Ohmura (1984). In unirradiated aragonite shell samples only three peaks are found: A(g=2.006), B(g=2.0027) and C(g=2.0008). In irradiated samples another two relatively weak signals appear: E(g=2.0022) and D(g=1.995) (Fig. 3).

Normally when analysing aragonite shell only peak C is suitable for determination of ED values as it is usually the only one showing a linear response in intensity to irradiation doses over a wide range of values. The signal also has a sufficiently long mean life to continue to increase in intensity over periods of up to 500,000 years or more. In rare cases, peak A can be used successfully for determination of ED values, for example by Goede and Hitchman (1987) for dating archaeological sites in southern Africa utilizing the aragonitic marine gastropod *Turbo sarmaticus*. However, in this present study, peak A was found not to be suitable for dating even when the closely related species *T. undulatus* and *T. torquata* were used.

ESR dating of aragonite shell has been used as a numerical dating method. The dose received by the sample consists of an internal component due to the presence of radioactive impurities within the sample and an external component due to radiation from the surrounding environment including a small component from cosmic radiation. If both components can be measured the age can be calculated by:

$$\text{Age} = \text{ED/annual dose rate}$$

While some successes have been claimed using the technique as a numerical method of dating aragonite shell (Ikeya and Ohmura, 1984; Hütt *et al.*, 1985; Katzenberger and Grün, 1985; Radtke *et al.*, 1985), there remain questions about the mean life of the peak normally

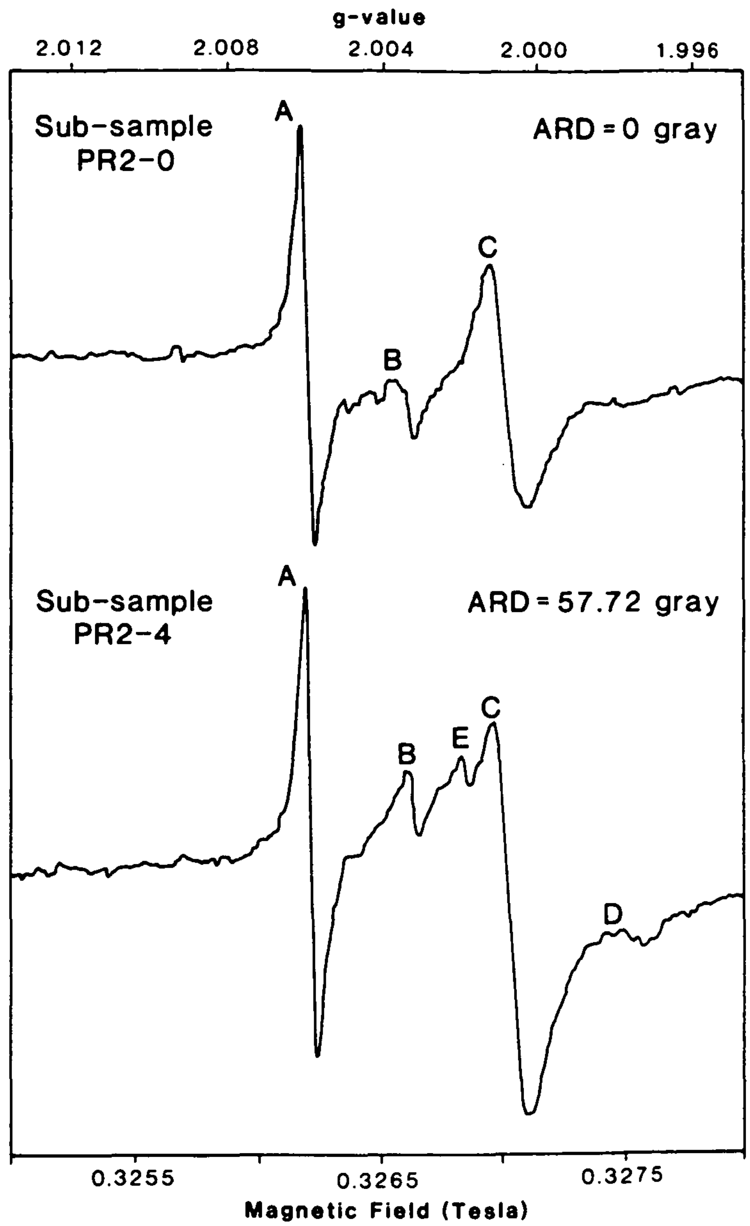

Fig. 3 The natural ESR spectrum of PR2 is compared with a sub-sample that has received an artificial gamma irradiation dose (ARD). Changes in peak C intensity are used to determine the equivalent dose (ED).

used for dating (Goede and Hitchman, 1987). There are also problems involved in the measurement of external dose and assumptions have to be made about the constancy of the radiation environment over the period of time the sample has been preserved. Since neither the shell nor its sedimentary environment are normally closed systems with respect to uranium compounds, such assumptions are inevitably suspect. Many of the problems involved in numerical dating by ESR can be reduced by using the technique as a relative dating method. It is very important to compare only similar sites and use only shells with a low uranium content (< 1 p.p.m.) so that inter-site variability in both external and internal dose rate are minimised.

Peak C is the one normally used for dating. In aragonite shell, relative intensities of peak C can be determined by measuring peak height. Strictly speaking, peak intensity is determined by the area under the curve but since the signal width is independent of dose it is necessary only to measure peak height. The intensity of the signal does not bear a fixed relationship to the radiation dose received since different samples have C peaks that vary in their sensitivity to irradiation. Variations in sensitivity are believed to be due to the presence of organic impurities. It will be shown in this study that sensitivity can bear an inverse relationship to the age of the sample.

SAMPLE PREPARATION AND ANALYSIS

In order to determine the ED value of a sample the following procedure is carried out. Samples of shell are etched in 10% acetic acid, washed repeatedly in distilled water and then dried at room temperature. The dried sample is crushed in a swing mill and the size fraction 125–250 μm separated out by sieving. The grains are etched in 10% acetic acid to remove surface defects that, following gamma-irradiation, produce a spectral peak with a g value sufficiently close to peak C to cause interference. The problems caused by surface defects have been demonstrated for calcite by Smith *et al.*, (1985) but they apply also to aragonite.

The selected size fraction is sub-divided into five sub-samples each weighing approximately 150 mg. One sub-sample is left in the natural state while the remaining four are exposed to regular increments of gamma radiation from a ^{60}Co source. This exposure is referred to as the artificial radiation dose (ARD) and is measured in grays. The dose rate is kept low (< 0.1 gray/h) to avoid the development of spurious defect peaks. Samples are always stored for at least a week before being measured to allow fading of any possible short-lived ESR peaks induced by irradiation.

Sub-samples are individually analysed on an ESR spectrometer (JOEL JES-FE 3X) using ambient temperatures at 100 kHz with a magnetic field modulation of 4×10^{-5} T, a microwave power of 5 mW and an amplitude of 1000. Each measurement is repeated four or five times and the mean taken. The peak C intensity of each sub-sample is then plotted against the corresponding ARD (Fig. 4). The points invariably plot along a straight line and a linear regression line is fitted. The distance between the origin and the point where the regression line intersects the horizontal axis determines the ED value of the sample.

Since ED determination requires considerable extrapolation of the observed relationships it is important to determine the degree of error involved in its estimation. The method used calculates the 95% confidence limits for each ED value using the technique recently advocated by Franklin (1986) for TL-dose data following a procedure originally proposed by Mandel (1964).

As long as fossil shells do not show strong, highly variable enrichment in uranium and come from similar sedimentary environments their ED values can be used to group them into distinct age related clusters. A clustering approach has long been used in amino-acid dating. An early example is given by Mitterer (1974) who was able to group analyses of marine fossil molluscs in southern Florida into seven discrete age related groups. In this

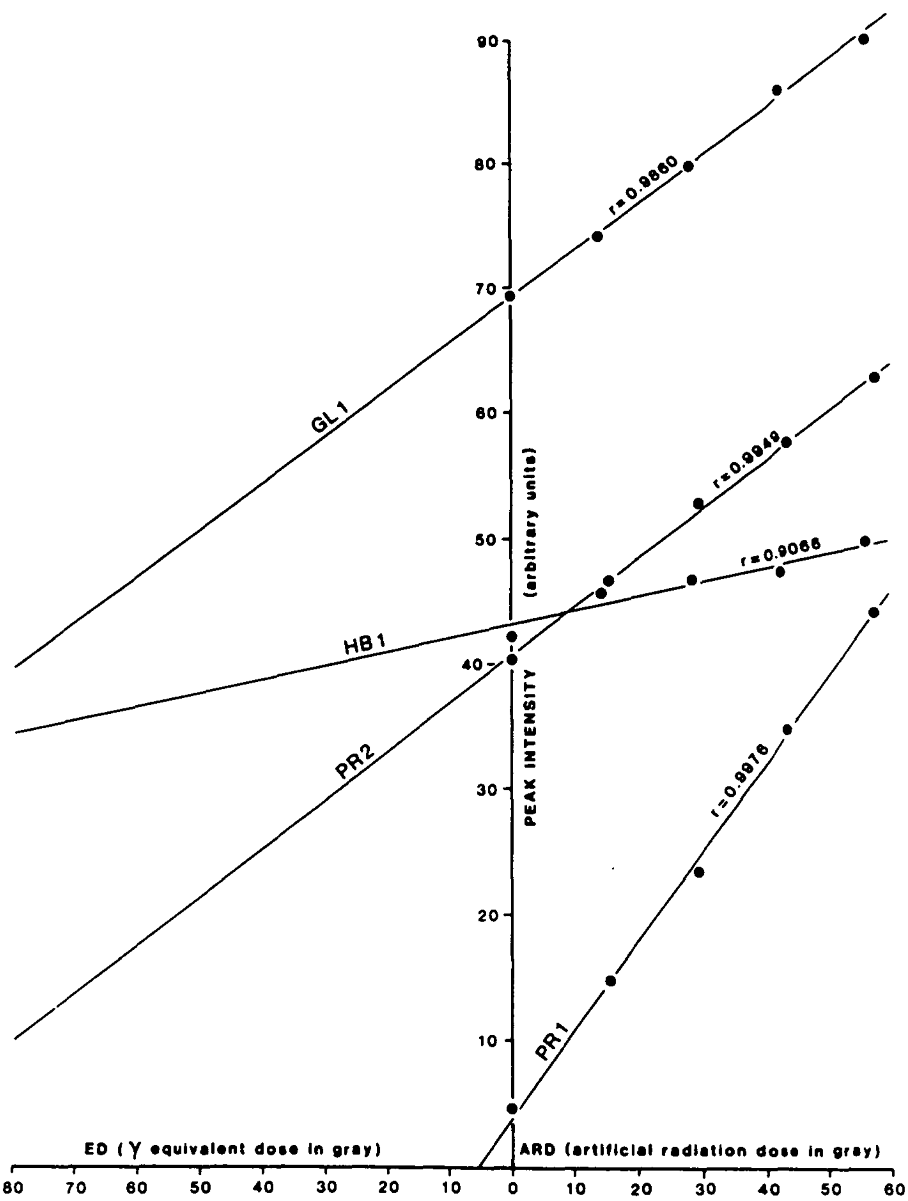

Fig. 4 Peak C intensity plotted against ARD for four samples of *T. undulatus* in order to determine the ED. Due to scale problems only the ED of sample PR1 is shown. Note decreasing sensitivity to gamma radiation in older samples.

study such groupings will be referred to as ED zones in close analogy with the term amino-zones as used by Murray-Wallace and Kimber (1987) in a recent amino acid racemization study of Quaternary marine molluscs in South Australia. Such zones are basically a tool for grouping the sediments into chronostratigraphic units to construct a stratigraphic framework. The technique is here termed ED stratigraphy (cf. aminostratigraphy; Miller *et al.*, 1979).

The author does not imply that ED values are in any way comparable to amino-acid racemization ratios. The latter are predominantly influenced by time and temperature history.

When all sites examined are in the same region the temperature factor can be assumed to be uniform.

ED values on the other hand are influenced by time and the radiation dose rate. The latter can change with time because of the potential mobility of uranium salts in the presence of water and the possible loss of some members of the uranium decay chains such as radon and radium. The concept of ED zones should only be applied to similar sites.

SAMPLE SITES AND SAMPLE COLLECTION

Shell samples suitable for analysis must consist of aragonite rather than calcite. Calcite ESR spectra are strongly affected by the presence of intense Mn^{2+} lines. One of these lines interferes with the C peak making it difficult to determine its intensity. Although some progress has been made in dealing with this problem (Ninagawa *et al.*, 1985), calcitic shells are best avoided. The mineralogy of samples was determined by infrared spectrophotometry.

There is an advantage in using the same species from all sites in a comparative study since shells of different species may occasionally show different spectral characteristics. In this study that was not possible since both high energy coastal and low energy estuarine sites were being investigated. On coastal sites the opercula of the marine gastropod *Turbo (Subninella) undulatus* were used. At two Pleistocene sites its locally extinct relative *Turbo (Ninella) torquata* was also analysed. Because of their shape the opercula of this genus often remain intact in high energy wave environments. The massive nature of the shells of this genus also reduces susceptibility to enrichment or leaching of uranium salts. The bivalve *Anadara* sp. was found at one site and because of its special interest as a possible Last Interglacial index fossil for the area (Gill, 1977) it was also analysed.

At the two estuarine sites examined the only two species suitable for ESR analysis were the bivalves *Irus crenatus* and *Mytilus edulis planulatus* (an edible sub-species of mussel). Both were used. *Irus crenatus* provides excellent material because of its thick shell but was relatively uncommon. *Mytilus* has a calcitic outer shell and an aragonitic inner shell. In fossil specimens the two are readily separated. However, the inner shell was often in a poor state of preservation. Large samples had to be collected because poor preservation caused a considerable loss of material in the preparation process. Description of the species used in this study can be found in Ludbrook (1984).

The following is a list of sample sites and the species collected at each:

PR1— Opercula of *T. undulatus* collected from a Holocene midden on the headland immediately adjacent to West Stack near Point Ritchie (Fig. 2). A ^{14}C date of 1,000 ± 200 a B.P. (SUA 1615) on aragonite shell (*Turbo undulatus*) has been obtained. Map ref. 316483.

PR2— Opercula of *T. undulatus* collected from the Point Ritchie site on West Stack (Fig. 2). The site consists of a scatter of broken shell fragments cemented to the sloping calcreted surface of a slumped block of aeolian calcarenite (Figs. 5 and 6). Prescott and Sherwood (1988) have given a description of the site and suggest that the shell accumulation may represent an Aboriginal midden. If its human origin can be confirmed it would be by far the oldest archaeological site known in Australia. A ^{14}C date on aragonite shell (*Turbo undulatus*) gave an age of 35,700 ± 500 a B.P. (SUA 2491)

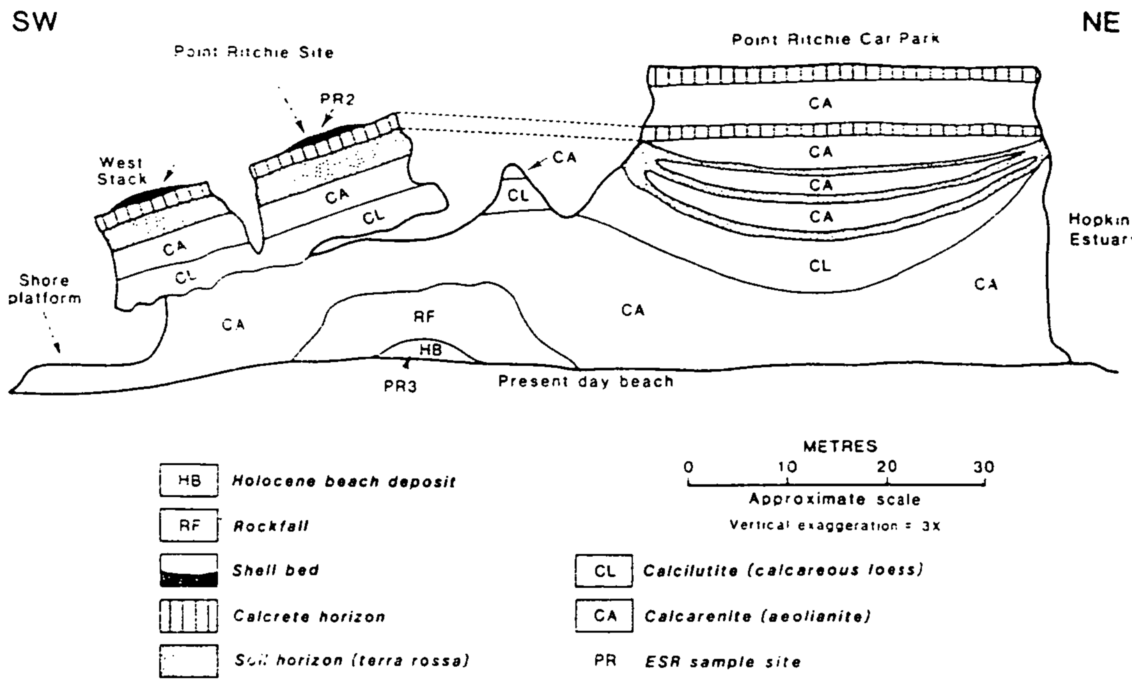

Fig. 5 Fieldsketch of Point Ritchie coastal cliffs showing relationships of sedimentary units, buried soils and calcrete horizons. Locations of samples PR2 and PR3 are indicated. Fieldsketch is redrawn and modified from Prescott and Sherwood (1988). The position of sample PR4 is not shown as it has been collected from a wave-cut notch in East Stack in front of the right hand portion of the section shown in the field sketch. The notch has been cut in the stratigraphic equivalent of the lowest calcarenite unit.

Fig. 6 Point Ritchie 'midden' site at West Stack. A layer of fragmented shell, predominantly of *Turbo undulatus*, has been cemented to a calcrete substrate. The site has been interpreted as a Last Interglacial aboriginal midden and a TL date of 80,000 + 25,000/ - 15,000 a B.P. obtained for quartz grains extracted from the calcarenite matrix. Sample PR2 collected here. For location see Figure 5.

and a date on charcoal yielded an age of 34,000 ± 800 a B.P. (SUA 2679). They are regarded as minimum ages as a TL age of 80,000 + 25,000/ - 15,000 a B.P. (WRIS/IC) was obtained for 100 μm quartz grains taken from the calcarenite matrix at the site (Prescott and Sherwood, 1988).

Two discoloured cobbles, suspected of being hearthstones yielded TL ages of 160,000 ± 25,000 a B.P. (WR4F) and 132,000 ± 11,000 a B.P. (WR4B). The age discrepancy between the sediment TL date and the two cobble dates suggests that the cobbles were either not hearthstones or were not sufficiently heated to reset the TL clock (Prescott and Sherwood, 1988). The origin of the deposit remains in doubt. Map ref. 316483.

PR3— Opercula of *T. undulatus* collected from a presumed Holocene storm beach deposit exposed during winter at the level of spring tides on the eastern side of West Stack (Figs. 2 and 5). Map ref. 316483.

PR4— Opercula of *T. undulatus* collected from a notch filling of shell-rich beach sediment with rounded cobbles that crops out on the side of East Stack at Point Ritchie approximately 2 m above the level of spring tides (Fig. 2). Map ref. 317483.

PR5— Opercula of *T. undulatus* collected from a lens of marine sediment in an aeolianite outcrop exposed approximately 70 m Northeast of East Stack along the bank of the Hopkins River estuary (Fig. 2). The aeolianite at both this and the last site has been mapped as Port Fairy Calcarenite and is believed to be of Last Interglacial age (Gill, 1977). Map ref. 317484.

GL1— Opercula of *T. undulatus* collected from a drain cut through a raised storm beach ridge up to 4 m above sealevel near Goose Lagoon on the western side of Port Fairy (Fig. 2). A species list of the shell content of the site has been presented by Gill (1971). A U/Th date date of 101,000 ± 2000 a B.P. (INS-U-24) on *T. torquata* has been obtained indicating a Last Interglacial age for the site. Map ref. 030509.

GL2— Columella of *T. torquata* from the same site as GL1. The columella was used as no opercula belonging to this species could be found.

TC— Opercula of *T. undulata* collected from an eroding midden at The Crags west of Port Fairy (Fig. 2). The midden is interbedded with unconsolidated calcareous dune sands that show minimal soil development indicative of a Holocene age. Map ref. 964523.

HB1— Opercula of *T. undulata* collected from the Hopkins Bridge site (Fig. 2). High energy beach sediment is exposed in a notch cut at the base of an aeolianite cliff just above high water mark on the eastern side of the Hopkins River estuary 600 m upstream from Hopkins Bridge. The notch is cut into a Pleistocene aeolianite sequence (Sunnyside Aeolianite). The site is discussed by Gill and Amin (1975) who report a U/Th date of about 400,000 a B.P. on aragonitic mollusc shells. The date is more appropriately regarded as infinite. Map ref. 322493.

HB2— Operculum of *T. torquata* from the same site as HB1.

HB3— Single valve of *Anadara* sp. from the same site as HB1.

LI2— Aragonitic inner shell of *Mytilus edulis planulatus* from heavily calcreted estuarine calcarenites rising up to 6 m above river level exposed in a well preserved terrace.

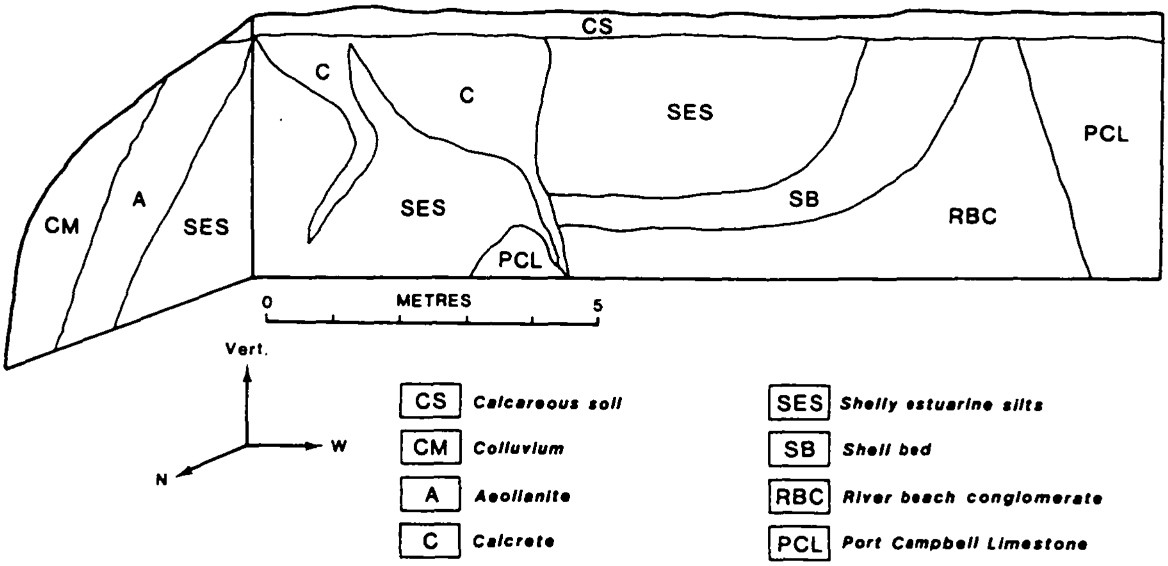

Fig. 7 Hopkins Estuary site. A thick sequence of shelly sediment rich in *Mytilus edulis planulatus* and *Balanus variegatus* overlies Tertiary limestone. The site was originally interpreted as an aboriginal midden and is at or beyond the range of ^{14}C dating. Samples HE2 and HE5 were collected from both units SB and SES in order to obtain sufficient material for analysis.

The collecting site was located on the southern bank of the Hopkins River across and 300 m downstream from the Warrnambool Institute of Advanced Education (Fig. 2). Gill (1977) regarded these deposits as Last Interglacial in age and time-correlates of the Port Fairy Calcarenite. Map ref. 336493.

LI3— Shell fragments of *Irus crenatus* collected from the same site as L12.

HE2— Aragonitic inner shell of *Mytilus edulis planulatus* from the Hopkins Estuary site (Fig. 2). The site consists of an accumulation of shell-rich sediment overlying Port Campbell Limestone (Fig. 7). The sediments show evidence of slumping. Cutting across the outcrop are two steeply dipping sheets of calcrete that appear to have originated as wind blown silt filling in fissures. The site was originally interpreted as an Aboriginal midden of Last Interglacial age (Gill, pers. comm.). Common estuarine species present are *Mytilus edulis planulatus* and *Balanus variegatus* with rare shells of *Irus crenatus*. Four ^{14}C dates have been obtained. *Mytilus edulis planulatus* shells have yielded ages of 41,000 + 3,200/ - 2,300 and > 51,000 a B.P. (SUA 2204, 2405). *Balanus variegatus* shells have provided ages of 40,400 + 2,400/ - 1,900 and 47,800 + 2,200/ - 1,700 a B.P. (SUA2233, 2513). They are considered to represent minimum ages. A detailed description of the site is to be published by Gill *et al.* (in prep.). Map ref. 379480.

HE5— Shell fragments of *Irus crenatus* collected from the same site as HE2.

RESULTS OF ANALYSES

The analytical results are set out in Table I. Uranium analyses are included to give an indication of possible enrichment that may have taken place. Goede and Hitchman (1987) have previously shown that samples with >1 p.p.m. uranium may pose problems when ESR is used as a relative dating method. None of the samples reaches this level. To determine the uranium

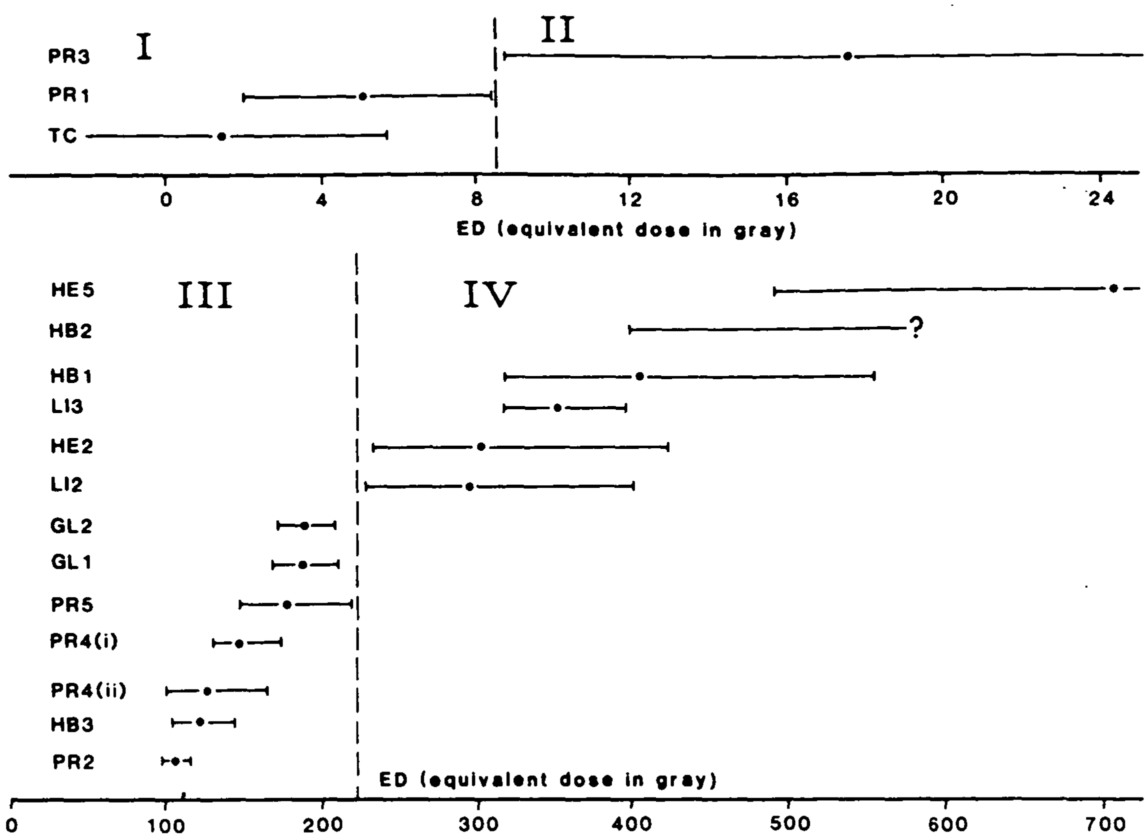

Fig. 8 ED values of samples shown with 95% confidence limits grouped into four ED zones.

content of modern opercula of *T. undulatus*, four specimens collected from Childers Cove, 15 km southeast of Point Ritchie, were analysed. Their uranium content proved to be rather variable with a range from <0.04 to 0.40 p.p.m. and a mean value of 0.33 p.p.m. The uranium content of the ancient mollusc samples has a range from <0.04 to 0.88 p.p.m. (Table 1). This indicates that little or no post-depositional uranium enrichment has occurred and suggests that reliance may be placed on the relative dates obtained by ESR.

When the ED values are plotted with their 95% confidence limits they fall into four groups without any overlap of values at the 95% level (Fig. 8). Group I consists of two samples collected from Aboriginal midden sites. They are indistinguishable from modern samples in that no spectral peaks are visible above the background noise. They are clearly late Holocene in age. The result for PR1 is in good agreement with a ^{14}C date of 1,000 ± 200 a B.P. (SUA 1615) on *Turbo undulatus*.

Group II includes only the single sample from the storm beach deposits on the eastern side of West Stack. Since Holocene samples generally fall in the range 0-20 gray this is likely to be Holocene. It was probably deposited soon after the sea reached its present level. Gill (1987) has claimed evidence for a +2 m sealevel at 6,000 a B.P. and a +1 m sealevel at 4000 a B.P. in Western Victoria but this deposit does not require a higher sealevel.

Group III has ED values ranging from 106 to 189 gray. They are much older than Groups I and II and are interpreted as Last Interglacial in age. The literature shows that Last Interglacial

TABLE I

LIST OF ANALYTICAL RESULTS

Sample Number	*Mollusc species*	*Site Name*	*Equivalent dose (gray)*	*Confidence limits 95%*	*Uranium content p.p.m.*	*ED zone*
PR1	*Turbo undulatus*	Point Ritchie	5	2.0-8.4	<0.04	I
PR2	*Turbo undulatus*	Point Ritchie "midden"	106	99-115	0.08	III
PR3	*Turbo undulatus*	Point Ritchie	18	8.7-27.2	0.48	II
PR4(i)	*Turbo undulatus*	Point Ritchie	149	130-174	0.48	III
PR4(ii)	*Turbo undulatus*	Point Ritchie	126	100-165	0.44	III
PR5	*Turbo undulatus*	Point Ritchie	176	146-218	0.32	III
GL1	*Turbo undulatus*	Goose Lagoon	187	168-210	0.60	III
GL2	*Turbo torquata*	Goose Lagoon	189	173-207	0.84	III
TC	*Turbo undulatus*	The Crags	2	-2.5-5.7	0.04	I
HB1	*Turbo undulatus*	Hopkins River Bridge	406	316-555	0.48	IV
HB2	*Turbo torquata*	Hopkins River Bridge	>>400	-	0.88	IV
HB3	*Anadara* sp.	Hopkins River Bridge	122	104-144	0.56	III
HE2	*Mytilus edulis planulatus*	Hopkins Estuary	304	232-425	0.08	IV
HE5	*Irus crenatus*	Hopkins Estuary	719	492-1299	0.24	IV
L12	*Mytilus edulis planulatus*	Estuarine terrace	295	228-402	0.12	IV
L13	*Irus crenatus*	Estuarine terrace	353	316-397	0.48	IV

shells usually have EDs between 100 and 200 gray (Hewgill *et al.*, 1983; Katzenberger and Grün, 1985, Goede and Hitchman, 1987).

The two Goose Lagoon samples are from a storm beach ridge. Gill (pers. comm.) suggested that the feature is related to a +4 m Last Interglacial shoreline which he correlated with marine isotope stage 5c on the basis of an unpublished $^{230}Th/^{234}U$ date of 101,000 ± 2,000 a B.P. (INS-U-24) on *Turbo torquata.* Such dates are not very accurate because the shells do not behave as chemically closed systems after the death of the organism (Schwarcz, 1982). Kaufman *et al.* (1971) have examined 61 $^{230}Th/^{234}U$ mollusc dates where reliable numerical ages were independently available. They found that the estimated ages were correct in 17 cases, significantly too high in 11 cases and significantly too low in 33 cases. If his sample is representative, there is at least a 50% probability that the Goose Lagoon date significantly underestimates the true age of the site. The high ED values of the Goose Lagoon samples within Group III make correlation with isotope stage 5e more likely. If correct, the storm ridge may be correlated with a high sealevel stand that elsewhere has been dated between 125,000 and 140,000 a B.P. (Chappell, 1983; Kaufman, 1986). The highest ED values in Group III are the two Goose Lagoon samples and PR5. The ED values of samples PR4 and PR2 are lower than those of the two Goose Lagoon samples and sample PR5. The time relationship of PR4 and PR2 cannot be established on stratigraphic grounds but both are obviously younger than the lower aeolianite unit shown in Fig. 5. Unlike the other samples in Group III, PR2 does not indicate the existence of a sealevel as high or higher than that of the present since the shells may have been brought to the site as a result of human or animal activity. The stratigraphy of Point Ritchie and the TL dating of the site is discussed by Prescott and Sherwood (1988). Their TL date of 80,000 + 25,000/ - 15,000 a B.P. is in good agreement with the ESR analysis and invites correlation with marine isotope stage 5a.

Also in Group III is the *Anadara* sp. sample (HB3) from the Hopkins River Bridge site. While this falls clearly into Group III, the other two samples from the site, *T. undulatus* and *T. torquata* are much older as they show ED values in excess of 400 gray. Gill and Amin (1975) reported a $^{230}Th/^{234}U$ date on aragonitic molluscs from this site of about 400,000 a B.P. which should be regarded as an infinite age. The ESR results strongly suggest that there is material of two different ages at this site and a close re-examination of its stratigraphy is called for.

It is ironic that the $^{230}Th/^{234}U$ date obtained by Gill and Amin (1975) from the Hopkins River Bridge site was used by Gill (1977) as evidence that *Anadara* sp., which had not previously been found in beds older than Last Interglacial, had been present on the west Victorian coast as long ago as 400,000 a B.P. It now appears that the only *Anadara* sp. shell we were able to collect at the site is almost certainly Last Interglacial in age. A $^{230}Th/^{234}U$ date on other *Anadara* sp. shells from the site would help to settle the conflict of evidence.

Group IV includes the two *Turbo* samples from the Hopkins River Bridge site as well as the four *Mytilus* and *Irus* samples from the estuarine terrace (LI) and Hopkins Estuary (HE) sites. All of these samples have ED values in excess of 290 gray and must be regarded as at least Middle Pleistocene in age. With the possible exception of sample HB2, they show no evidence of uranium enrichment. Samples from the LI and HE sites cannot be distinguished from samples HB1 and HB2 from Hopkins River Bridge. All three sites are likely to be of the order of 400,000 a B.P. in age or older. This is further evidence for a non human origin of the HE site. (Gill *et al.*, in prep.).

ED values provide a division of the samples into four ED zones that can be regarded with some confidence as representing four discrete chronostratigraphic horizons. It is interesting to observe that when the nine samples of opercula of *Turbo undulatus* are examined, there is a strong correlation between the ED values and the sensitivity of the C peak to irradiation (Fig. 9). The regression equation of the line of best fit between the two variables is:

$$S = 0.8058 - 0.2406 \log ED \ (r = 0.941)$$

where S is the sample sensitivity to gamma irradiation. Student's t test (d.f.=7, t=7.3231) indicates that the correlation is highly significant. Extrapolation of the relationship suggests a saturation dose for the peak intensity of approximately 2200 gray. Katzenberger and Grün (1985) obtained a similar strong correlation in an ESR study of circumarctic molluscs and suggested that this was due to a non-linear increase of peak C intensity upon exposure to gamma irradiation. However, linear regression between ED and C peak intensity for many individual samples has produced extremely high correlation coefficients which makes this explanation rather unlikely. Instead, it appears probable that the senstitivity of C peak intensity to gamma radiation is an age-related variable. Hence its strong correlation with ED values. The two variables can be used together to distinguish age groups (Fig. 9), at least in the case of the species *Turbo undulatus*.

CONCLUSION

ESR analysis is a powerful method of relative dating of aragonitic marine and estuarine mollusc shells and distinguishes between modern, older Holocene, Late Pleistocene, and older samples. The Point Ritchie and Hopkins Estuary sites have both been interpreted as Aboriginal middens and a Last Interglacial age has been suggested for both of them. This study shows

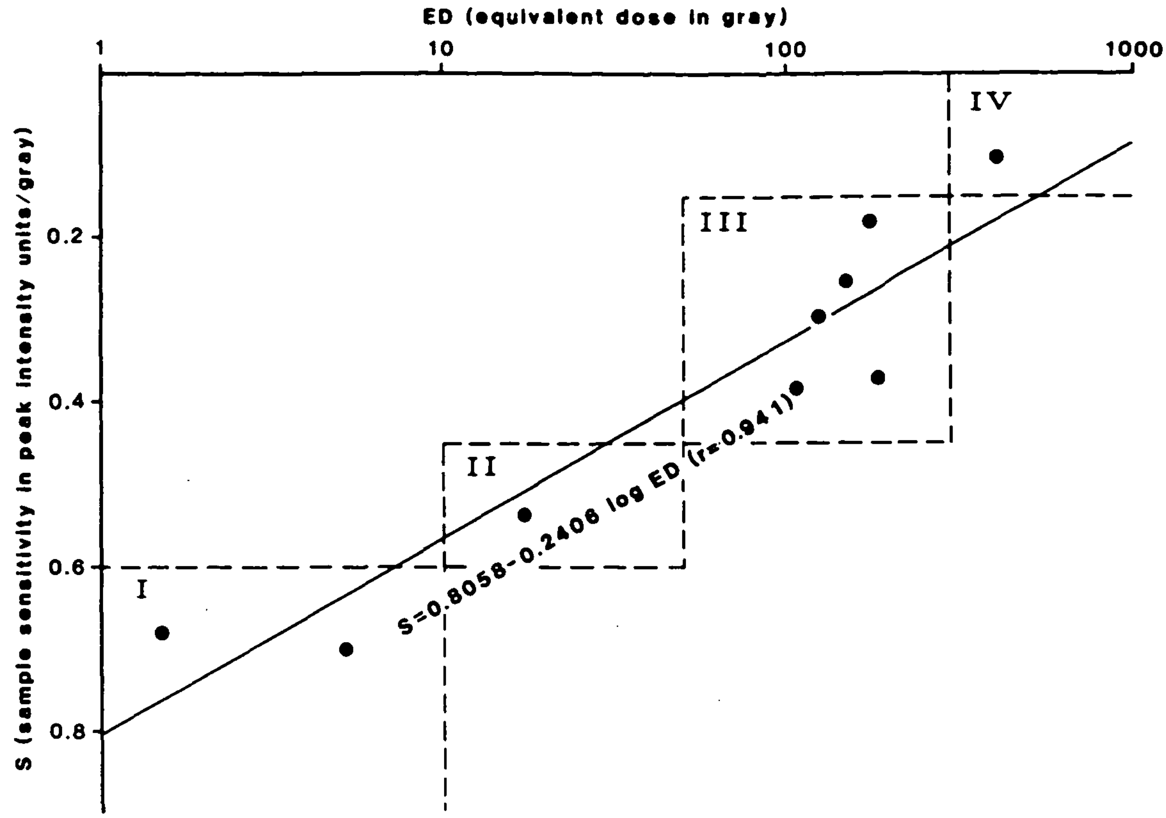

Fig. 9 The regression of sample sensitivity on ED showing the close relationship between the two for the species *T. undulatus*.

that while the Point Ritchie site (PR2) is undoubtedly late Last Interglacial in age, the Hopkins Estuary site (HE) is much older. The prominent estuarine terrace of the Hopkins River has also been regarded as Last Interglacial but appears to be of similar age to the pre-Last Interglacial Hopkins Estuary and Hopkins River Bridge sites.

However, at the Hopkins River Bridge site there is at least some marine shell of possible Last Interglacial age. This is evident from the low ED value obtained for the *Anadara* sp. (HB3) sample. This throws some doubt on Gill's (1977) suggestion that this species was present on the west Victorian coast as long ago as 400,000 a B.P.

Both ESR analysis and amino-acid racemization dating are valuable relative dating tools. In combination the two techniques can provide convincing evidence of age related groupings. It is important that the different nature of the two techniques is recognised and that only clearly separated clusters are distinguished.

ACKNOWLEDGEMENTS

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Pleistocene climatic change in Southern Australia and its effect on speleothem deposition in some Nullarbor caves

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ABSTRACT: Activity ratios of $^{234}U/^{238}U$, $^{230}Th/^{234}U$, and $^{230}Th/^{232}Th$ have been determined for calcite, gypsum and halite speleothems from caves of the Nullarbor Plain, mostly in the area N and NW of Mundrabilla Station, for the purpose of U-series dating. All calcite speleothems contain adequate amounts of uranium for dating, but some show an excess of ^{230}Th. Stratigraphic relationships indicate that there were at least three phases of calcium carbonate deposition in the Nullarbor caves. The calcite samples, with one possible exception, have ages in excess of ca. 400000 yrs BP. This suggests that no significant amounts of calcium carbonate deposition have taken place during the last 400 ka.

At present, active deposition of speleothems is restricted almost entirely to gypsum and halite. The only gypsum speleothem dated was found to have a finite age of ca. 185 ka. Six dates on a small halite speleothem containing insect and arachnid remains indicate that it formed rapidly during Holocene time.

JQS Journal of Quaternary Science

KEYWORDS: Calcite, gypsum, halite, climatic change, uranium series dating.

Introduction

The Nullarbor Plain, with its associated caves, is probably one of the most intensively studied karst areas in Australia. This is due especially to the research carried out by J.N. Jennings (Jennings, 1967a, 1967b; Lowry and Jennings, 1974). The region has a semi-arid climate and has a mean annual precipitation of between 150 and 250 mm, with a winter maximum due to frontal activity. There is a marked seasonal temperature range with hot (40°C max.), windy summers and average temperatures of 23°–26°C for the warmest month and 10°–12°C for the coldest month when frosts are common at nights. The mean annual temperature ranges from 17°–18°C and cave temperatures, where measured, range from 16°–18°C. The vegetation of the plain is dominated by shrubby steppe foliage consisting of halophytic plants. A shrubby xerophytic vegetation, dominated by eucalypts and acacias, is found in near-coastal areas and some steep-sided dolines (Dunkley and Wigley, 1967; Martin and Peterson, 1978).

The caves discussed in this paper are all located on the Bunda Plateau – a surface of slight relief developed on a flat-lying sequence of marine limestones ranging in age from Eocene to Miocene (Fig. 1). The plateau reaches a maximum elevation of 240 m in the northwest and declines both southwards and eastwards towards coastal cliffs that are up to 90 m high. In its central portion the Bunda Plateau is separated from the Great Australian Bight by the Roe Plains – a younger limestone surface cut into the Tertiary limestones and veneered by a thin mantle of Pleistocene marine sediments. The two surfaces are separated by a fossil seacliff that has become degraded and dissected to form the Hampton Range.

The Nullarbor Plain has no surface drainage, but aerial photography studies (Jennings, 1967a; Lowry and Jennings, 1974) have shown a number of relict stream courses traversing the northern and western parts of the Nullarbor karst (Fig. 1). A field investigation of one of these channels, The Dip, was made by Jennings (1967b) who found that well developed meanders leave no doubt about its origin. The channels are interpreted as relicts formed at a time of greater effective precipitation. A watertable of low gradient underlies most of the plain at depths ranging from 30 m in the north to 120 m near the southern margin of the Bunda Plateau. Deep caves are defined as those that reach down to the present day water table (e.g. Mullamullang Cave). Groundwater movement is quite slow and salinity increases towards the coast where a TDS content >5000 ppm is not uncommon.

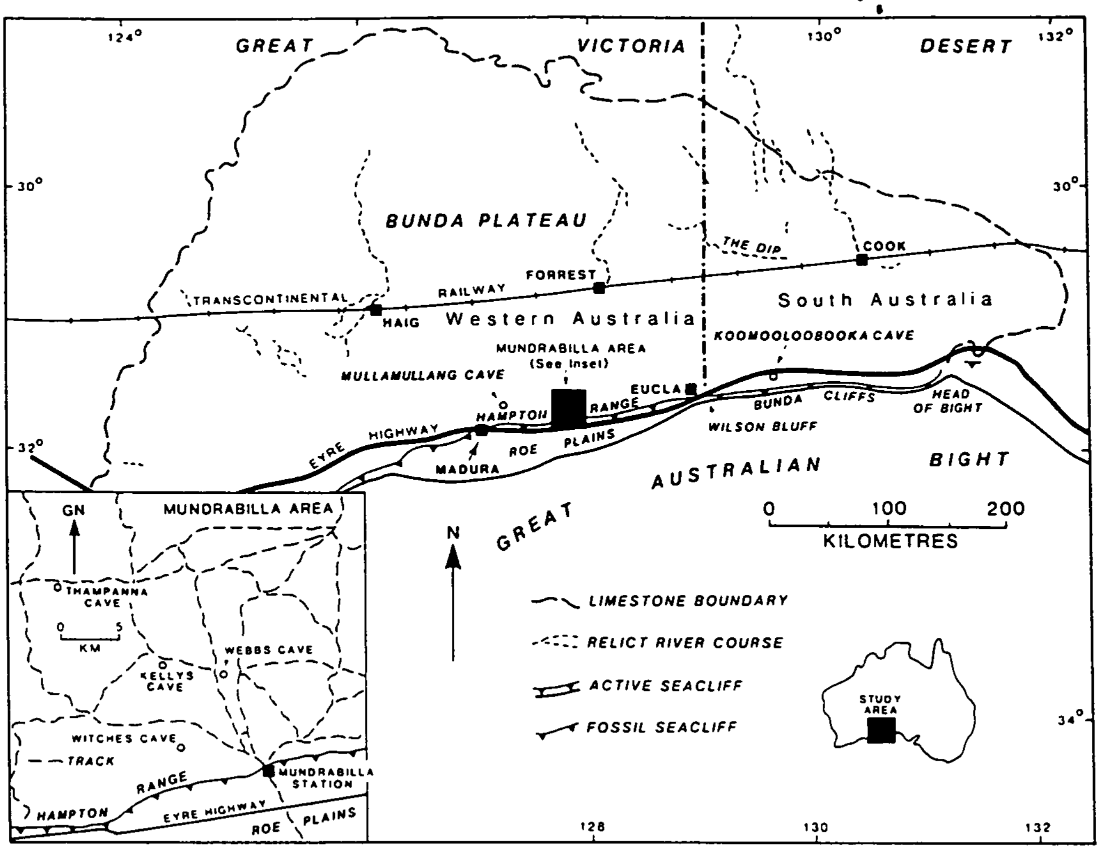

Figure 1 Locality map of Nullarbor karst area with cave localities shown.

Considering the area of the Nullarbor karst, at least 200 000 km^2, known caves are relatively scarce. Matthews (1985) lists 223 numbered karst features, but not all of these are entrances to caves. Most commonly entrances are either vertical solution shafts or are located at the base of collapse dolines, frequently with vertical or overhanging sides. The distinction between deep caves (45–120 m deep) and shallow caves (6–30 m deep) was originally made by Thomson (1949). This was later seen to be a simplification (Lowry and Jennings, 1974) as there are some caves of intermediate depth (e.g. Thampanna Cave). Nevertheless, it reflects the fact that cave enlargement has apparently taken place predominantly at two different horizons.

Fieldwork and the collecting of samples for uranium series disequilibrium dating were concentrated on four caves in the Mundrabilla area (Fig. 1), because the caves had been reported to be particularly rich in relict calcium carbonate speleothems. Two caves elsewhere on the plain were also investigated and sampled. They were Mullamullang Cave (N-37) and Koomooloobooka Cave (N-6).

Subterranean evidence for climatic change

Four Mundrabilla caves were visited (Webbs Cave, Kelly Cave, Witches Cave, Thampanna Cave, Fig. 1). Three of these contain abundant calcium carbonate speleothems, including stalactites, stalagmites, pool deposits, rimstone and flowstone. The same situation also prevails in Koomooloobooka Cave, but here speleothem fragmentation by salt weathering has been particularly severe. Carbonate deposition has not been abundant in Thampanna Cave, but a 1 m thick sequence of calcium carbonate pool deposits was found exposed in the roof and walls in one chamber. In section, it was observed that stalactites growing from the ceiling had become incorporated in the deposit and several others were found lying horizontally within it (Fig. 2). Accumulation of the calcium carbonate speleothems, that are clearly relict and not being actively deposited at present, would have required a lengthy period, or a number of periods, when effective surface precipitation was significantly greater than today, so that vadose percolation was sustained.

None of the calcium carbonate speleothems observed in Nullarbor caves are active today and they show no signs of recent activity. Many have been strongly affected by salt weathering involving wedging and disruption by sodium chloride crystals. The process has varied in intensity, causing extensive destruction by fragmentation of older speleothems in Koomooloobooka Cave, Witches Cave, and parts of Webbs Cave (Fig. 3). The weathering process by evaporative formation of halite appears to have been particularly effective in areas with strong air currents and where temperature and relative humidity are likely to have varied most, usually close to cave entrances.

Crystal wedging by salt has affected not only carbonate speleothems, but has also caused extensive weathering of bedrock inside the caves giving rise to small-scale cavernous weathering (tafoni). Larger-scale features produced by salt weathering were observed in Kellys Cave, where at least three roof domes have formed and deposited mounds of angular rock breakdown below ranging up to 3 m in height. In Webbs and Witches Caves, large calcium carbonate columns appear to

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Figure 2 A 1 m thick sequence of calcite pool deposits exposed by collapse in the wall of a low-roofed chamber in Thampanna Cave. As the deposit accumulated, stalactites hanging from the ceiling were incorporated. Broken fragments of others were observed in the section.

have provided some protection against ceiling attack by salt giving rise to downward projecting 'inverted pedestals' of bedrock supported by weathered column remnants.

From fieldwork in the caves, three distinct phases of calcium carbonate deposition have been identified, but more may be present. In several caves, especially Webbs, Kellys, and Koomooloobooka Caves, a phase of white calcite deposition is seen to have been preceded by an older phase of 'black' calcite deposition. Although it has been referred to as 'black' calcite there is a range of colour variation from dull black to dark brown. Colour in Nullarbor Plain speleothems has been investigated by Caldwell *et al.* (1982). A black calcite speleothem from Webbs Cave was found to contain a small but significant amount of organic carbon. The black colour of the calcite is considered to be due to disseminated humic matter. Further study of the nature of the organic content may throw some light on the vegetation of the plain at the time of deposition of the 'black' calcite. A longitudinal cross section through a stalagmite (KC) from Kellys Cave shows that, in this cave at least, the phase of 'black' calcite deposition was preceded by a phase of lighter brown, banded calcite (Fig. 4). The two phases are separated by a major corrosional disconformity, with the contact marked by a narrow band of white calcite.

The question of colour and also composition of organic matter in speleothems has been investigated elsewhere by Lauritzen *et al.* (1986) who found that coloured speleothems investigated by them contained up to 2000 ppm of organic matter.

A number of lines of evidence suggest that calcium deposition has not occurred for a long time in any of the caves sampled. Active drips were not observed on carbonate speleothems. However, very restricted deposition of carbonate is known from a few shallow caves with chambers that underlie large, shallow dish-shaped solution dolines. In Jimmys Cave (N-23), near the eastern margin of the plain, stalagmites up to

Figure 3 Partial fragmentation of relict calcite column in Witches Cave by salt weathering giving rise to a floor accumulation of angular fragments

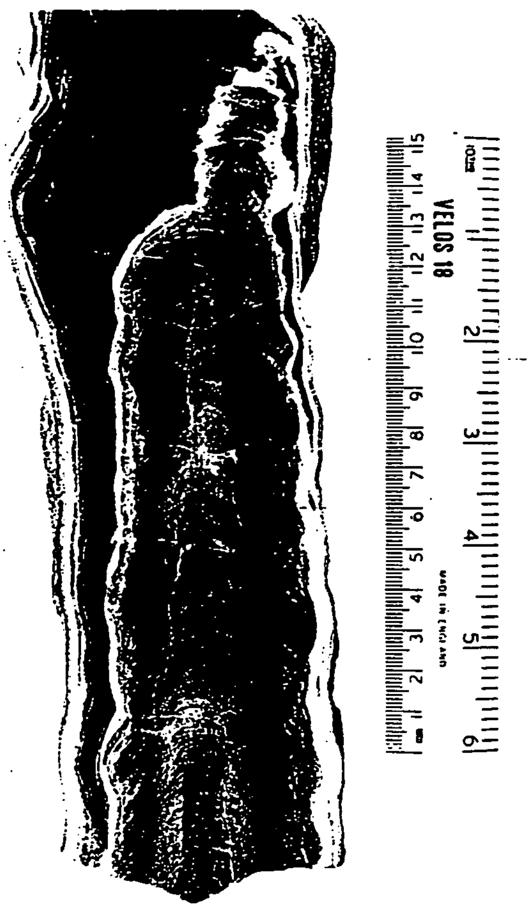

Figure 4 Longitudinal section through stalagmite (KC) from Kellys Cave shows two phases of dark-coloured calcite deposition separated by a significant period of corrosion.

70 cm tall are actively forming today and have grown on rock piles that are believed to have been constructed by aboriginal man (Davey, pers. comm.). This is regarded as an exceptional situation. In contrast there are several lines of evidence indicating a considerable age for the last period of significant calcium carbonate deposition.

1 There is a general absence of calcium carbonate in the deep caves, where only gypsum and halite speleothems occur. This suggests that either the deep caves had not yet formed, or more likely, that they had not yet been drained when calcium carbonate deposition ceased.
2 The occurrence of substantial speleothems of gypsum or halite superimposed on older carbonate speleothems is widespread. The evidence from Webbs and Kellys Caves (Fig. 5) is particularly convincing, but it is also seen in Thampanna Cave. Active deposition of halite was observed in Kellys Cave and active gypsum deposition in Thampanna Cave.
3 There is field evidence for considerable salt weathering of carbonate speleothems, especially in Webbs and Witches Cave (Figs 3 and 6). In Webbs Cave some stalagmites have strongly corroded tips that may be attributable to the effects of prolonged dissolution by bat urine.

The three phases of calcium carbonate deposition recognised so far clearly reflect the intermittent occurrence of conditions of significantly greater moisture availability than prevails at present. Flowstone and pool deposits in Webbs Cave (Fig. 5), Witches Cave, and Thampanna Cave (Fig. 2) clearly reflect the presence of long periods of standing water in the shallow caves. For example, the pool deposits in Thampanna Cave are unrelated to the present day morphology of the chamber in which they occur, but have been exposed by roof collapse. Other possible evidence of wetter conditions is provided by a pressure tube, evidence of dynamic phreatic flow, that connects parts of the cave (Fig. 7). In the absence of scallops it is not feasible to estimate the velocity of flow during the final stages of

Figure 5 Relict rimstone pools in Webbs Cave overgrown with some halite stalagmites and columns. Samples W-1 (halite) and W-4 (calcite) were collected in this area.

Figure 6 Phreatic tube approximately 30cm in diameter exposed in wall of Witches Cave. Lower part is filled with clastic sediment and carbonate flowstone formed under past conditions of greater moisture availability. Subsequent drier climatic conditions gave rise to salt weathering and angular fragments of limestone accumulated due to crystal wedging.

the tube's formation. It is not clear whether scallops failed to develop or were removed by subsequent salt weathering of the exposed bedrock. Rapid groundwater flow is not characteristic of the Nullarbor under the present climatic regime.

Diving in two of the deep caves (Weebubbie Cave and Cocklebiddy Cave) has recently revealed morphological features that indicate that they too have developed as a result of water flowing under pressure (Grodzicki, 1985). Scallop forms on underwater walls are reported from both caves. In Weebubbie Cave bellholes were also found in the roof of an underwater passage. Based upon the evidence. Grodzicki (1985) suggested that the deep caves formed under conditions of dynamic phreatic flow at a time when more humid conditions prevailed. In those parts of the deep caves that have been drained, the features produced by phreatic flow probably have been destroyed by roof collapse and salt weathering. An alternative view of the origin of at least one of the deep caves (Mullamullang Cave) has been suggested by Hunt (1970), who postulates that the main passage is due to collapse along structurally controlled belts of solution tubes. A problem is that in order to account for the size of the cave, it is necessary to postulate the occurrence of a number of primary phreatic networks stacked one above the other. Cavitation by collapse is thought to have extended well below the present groundwater table assisted by low sea levels with correspondingly low groundwater levels during periods of Pleistocene glaciation.

Whatever the origin of Mullumullang Cove, many Nullarbor caves, both deep and shallow, show clear evidence of wetter conditions in the past. However, without radiometric dating of speleothems, it has not been possible previously to choose between two major hypotheses about the timing and nature of the desiccation process that has affected the Nullarbor karst:

1 The process has been a long-term trend, such as can be seen in other areas of Southern Australia. It may have begun as early as the Miocene (Wasson and Clark, 1988) but pronounced aridity became a characteristic feature only during the last 500 ka.

Figure 7 Tube passage formed by phreatic flow in Thampanna Cave provides evidence of groundwater flow under more humid climatic conditions

2 The process is characteristically associated with interglacial conditions during the Quaternary because of a combination of high evaporation rates and low precipitation as is seen at present. Lowry and Jennings (1974) postulate that during cold phases of the Pleistocene there may have been greater moisture availability because 'effective precipitation, if not absolute precipitation, was in all probability greater than at present, though still low.'

Bowler and Wasson (1984) have summarised evidence for glacial-age environments of inland Australia. They show that, whereas dry conditions prevailed during the Last Glacial Maximum, many inland lakes were full most of the time between 40 and 25 ka suggesting conditions of significantly greater moisture availability than today. If this applies to the Nullarbor the situation would be analogous to that found in Namibia, where, ^{14}C-dating of speleothems in a small cave system near Rossingberge has shown that deposition of carbonate speleothems occurred between 40 and 25 ka despite the aridity of the present climate (Heine and Geyh, 1983).

If the Nullarbor karst has been significantly affected by Pleistocene pluvial conditions, that in all probability would have recurred repeatedly during Middle and Late Pleistocene times, we can confidently expect to find some carbonate speleothem deposition within the range of uranium series disequilibrium dating. An answer, as to which of the two hypotheses is the correct one, will have considerable implications relating to the length of time the West Australian flora and fauna of the wetter southwest have been isolated from Eastern Australia. It will also increase understanding about the timing of adaptation of the troglobitic invertebrate fauna of the caves to the present degree of aridity.

Radiometric dating

The $^{230}Th/^{234}U$ method of uranium-series disequilibrium dating of speleothems has proved to be a reliable technique for the dating of carbonate speleothems, provided that the uranium content is adequate and the speleothems remain a closed system to U and Th migration after deposition.

The dating procedure for carbonates has been discussed in detail by Harmon *et al.* (1975), Gascoyne and Schwarcz (1982), and Gascoyne (1984), amongst others. Since no alterations were needed to deal with halite or gypsum only a brief outline is given here. For best results speleothems should have a uranium content >0.1 ppm. Samples were dissolved in nitric or hydrochloric acid and radiochemically pure uranium and thorium were extracted from the sample by ion-exchange. Alpha spectrometry counting was used to measure the radioactivity of the various isotopes of uranium and thorium. The activity ratios $^{230}Th/^{234}U$, $^{234}U/^{238}U$ and $^{230}Th/^{232}Th$ were then calculated from background and blank corrected alpha spectra.

The first two ratios are used in the age formula, together with the known decay constants of ^{230}Th and ^{234}U, to determine the age of the sample. The ratio $^{230}Th/^{232}Th$ is used to determine the degree of detrital contamination of the sample. Where the ratio is small (<ca. 20), it is necessary to make a correction in order to obtain a correct age estimate (Schwarcz, 1980). Details of sample sites and sample collection are shown in Appendix 1.

Results of $^{230}Th/^{234}U$ Dating

Dating was attempted on eleven calcite samples and one of gypsum at the Scottish Universities Research and Reactor

Table 1 Uranium concentrations, activity ratios and calculated ages of Nullarbor speleothems

Sample no.	Location	Type	Mineralogy	U Conc. (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Calculated Age (ka BP)
W-4	Webbs Cave	Stalagmite	Calcite (w)	0.54	0.96 ± 0.01	1.00 ± 0.02	–	>530 c
W-6	Webbs Cave	Stalagmite	Calcite (w)	0.65	0.96 ± 0.02	1.03 ± 0.05	229	>480 c
K-2	Kelly Cave	Stalagmite	Calcite (w)	1.34	0.95 ± 0.01	0.93 ± 0.03	114	335 ± [illegible]
KE-1	Kelly Cave	Stalagmite	Calcite (b)	1.93	0.92 ± 0.01	1.01 ± 0.02	40	∞ d
KC-1	Kelly Cave	Stalagmite	Calcite (b)	1.23	0.93 ± 0.02	0.99 ± 0.06	112	>317 c
T-3	Thampanna Cave	Pool deposits	Calcite	0.32	0.86 ± 0.02	1.42 ± 0.09	77	Not calc.*
T-4	Thampanna Cave	Pool deposits	Calcite	0.36	0.92 ± 0.02	1.02 ± 0.03	32	∞ d
WIT-2	Witches Cave	Stalagmite	Calcite (w)	0.62	0.95 ± 0.02	1.18 ± 0.03	47	Not calc.*
WIT-3	Witches Cave	Flowstone	Calcite	0.38	0.94 ± 0.01	1.06 ± 0.03	60	>400
M-1	Mullamullang	Interstratal flowstone	Calcite	1.26	0.98 ± 0.02	1.16 ± 0.07	210	Not calc.*
KW-2	Koomooloobooka Cave	Stalagmite	Calcite (b)	0.50	0.99 ± 0.04	1.30 ± 0.08	71	Not calc.*
T-1	Thampanna Cave	Stalactite	Gypsum	0.06	1.52 ± 0.05	0.87 ± 0.07	18	185 ± [illegible]†
UEA299	Webbs Cave	Stalagmite	Halite	0.154	0.731 ± 0.015	0.031 ± 0.005	20	3.4 ± 0.6
UEA300	Webbs Cave	Stalagmite	Halite	0.126	0.752 ± 0.015	0.032 ± 0.006	36	3.7 ± 0.6
UEA301	Webbs Cave	Stalagmite	Halite	0.096	0.777 ± 0.029	0.011 ± 0.014	17	1.2 ± 1.5
UEA302	Webbs Cave	Stalagmite	Halite	0.108	0.743 ± 0.019	0.051 ± 0.019	270	5.7 ± 2.2†
UEA303	Webbs Cave	Stalagmite	Halite	0.110	0.726 ± 0.018	0.040 ± 0.005	8	4.4 ± 0.5
UEA304	Webbs Cave	Stalagmite	Halite	0.137	0.734 ± 0.018	0.016 ± 0.008	40	1.7 ± 0.9

* excess of ^{230}Th, † low thorium yield; w, white calcite; b, 'black' calcite; c, lower limit of 1-sigma age range where this is less then 650 ka; d, lower limit of 1-sigma age range is greater than 650 ka

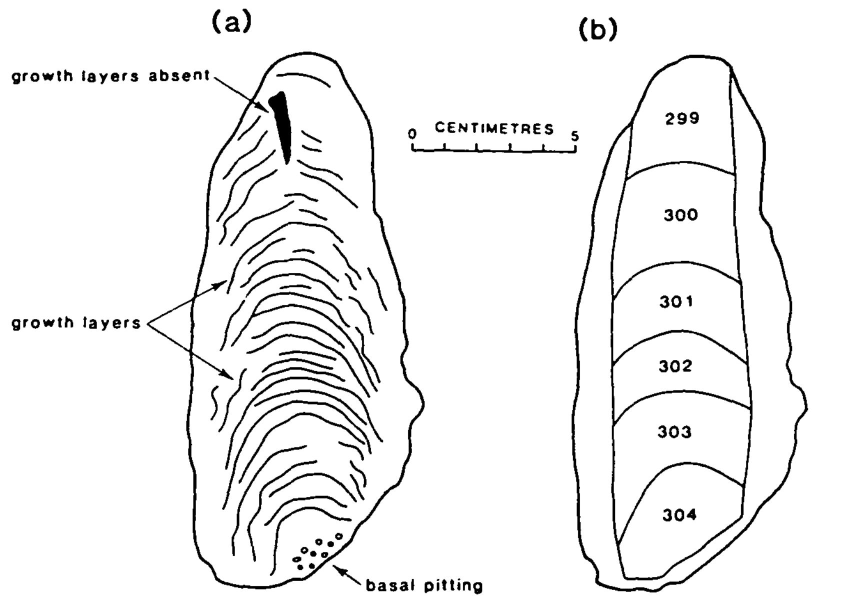

Figure 8 Longitudinal sections of halite speleothem (W-1). (a) shows pattern of growth layers consisting of thin grey translucent horizons separated by thick white opaque layers. Base and parts of the outer surface show evidence of pitting indicating some resolution. (b) shows how stalagmite core was cut to provide the six UEA halite samples for $^{230}Th/^{234}U$ dating. For details of analyses see Table 1.

Centre, whereas the six halite samples were analysed at the University of East Anglia. The uranium content of calcite speleothems was variable (0.32–1.93 ppm), but in all cases sufficient for radiometric dating. The $^{230}Th/^{232}Th$ activity ratios indicate that detrital contamination is relatively low. $^{234}U/^{238}U$ ratios for all calcite speleothems are <1.0, a feature which is quite unusual in speleothems, and likely indicates that the U in the vadose zone of the Nullabor at the time the carbonate speleothems were deposited was derived from the leaching of a source already depleted in U or that ^{234}U was leached preferentially to ^{238}U after deposition. Four samples showed an excess of ^{230}Th, suggesting that they have not remained closed systems with respect to uranium. This makes it impossible to define precise ages, but the samples clearly are of considerable age. Five of the remaining samples are at secular equilibrium with ages >400 ka. An exception is a white calcite sample from Kelly Cave (K-2) that gave an age of 335 ± [illegible] ka, close to the limit of the dating method. The non-equilibrium values of $^{234}U/^{238}U$ ratios in these samples indicate that they are younger than ca. 1.25 million years, but without a reliable independent estimate for the initial value of this ratio in the calcite speleothems, it is impossible to estimate their age more precisely. The results suggest that there has been no significant carbonate deposition in the Nullarbor caves for at least the past 300 000 yrs BP, and probably for more than 400 000 yrs BP.

The single gypsum speleothem (T-1) that was successfully dated has a very low uranium content, an indication of some minor detrital contamination, and gave a very low thorium yield (<10%). The resultant date of ca. 185 ka shows a large standard error and must be regarded as unreliable. It may indicate that deposition of sulphate speleothems has been occurring during the past 200 000 yrs.

Experiments, to ascertain if halite speleothems could be dated by U-series techniques, were carried out on six samples cut from a single 16 cm high stalagmite (W-1) from Webbs Cave. In longitudinal section this stalagmite clearly shows growth layering due to the fact that thin grey translucent layers alternate with much thicker white opaque layers (Fig. 8, see Table 1 for details of analyses). The very young age (<6 ka) of the samples, combined with the relatively low uranium contents and some detrital thorium contamination, makes a precise estimate of age impossible. While the reliability of individual dates is low, the samples agree in giving late Holocene ages. If we disregard UEA302 because of its low thorium yield and sample UEA303, because it shows some evidence of detrital thorium contamination, the mean age of the four remaining samples is 2.5 ± 1.2 ka. There is no real trend of dated age with height above the base, so the stalagmite probably grew within a period no longer than the time resolution of the dating, i.e. 1000–1500 yrs.

Interesting features of the data for the halite samples are the fairly consistent uranium content (ca. 0.1 ppm) and very consistent $^{234}U/^{238}U$ ratio (ca. 0.74). This $^{234}U/^{238}U$ ratio of 0.74, is much less than the value of 1.14 normally found in seawater. This suggests that the source of uranium in the stalagmite is not directly from sea spray or derived from marine salts in rainfall. One of these may be the source of the chloride in the stalagmite, but the activity ratio much less than unity suggests that the percolating water dissolved uranium from a second source which had already been subject to extensive leaching (Lively *et al.*, 1979). Possible sources are the limestones above the cave or the calcrete capping that covers most of the surface of the plain. The difference between the $^{234}U/^{238}U$ ratios of the carbonate samples (ca. 0.9–1.0) and that of the halite specimen (0.74), may indicate extensive leaching of U from the limestone and/or calcrete capping during the minimum 300 000–400 000 year interval between deposition of these two types of speleothems.

Faunal remains in halite stalagmite

An unexpected discovery was made when the halite samples from Webbs Cave were dissolved during the dating procedure, and some insect and arachnid remains were recovered. These were identified by Dr M. Gray of the National Museum (Sydney) as belonging to the beetle genus *Ptinus* (Family Ptinidae) and the cave dwelling pseudoscorpion *Protochelifer cavernarum aitkeni* Beier (Family Cheliferidae). *Ptinus exulans* is a cosmopolitan species identified from other Nullarbor Caves and is commonly associated with bat guano (Hamilton-Smith, 1967). The pseudoscorpion is a cave-dwelling sub-species described by Beier (1968) from specimens collected in Abrakurrie Cave, a deep cave on the Nullabor Plain located approximately 60 km east of Webbs Cave.

Discussion

Uranium series analyses of calcite speleothems indicate that significant deposition of calcium carbonate had ceased by ca. 400 ka. The dates suggest a prolonged period of aridity in the later Quaternary.

Dating of gypsum and halite speleothems is at present restricted to one of each. The gypsum date hints at considerable antiquity of at least some gypsum deposition but must be regarded as unreliable due to its low uranium content and low thorium yield. Multiple dates on a small halite stalagmite indicate rapid growth in the Late Holocene.

A much more extensive programme of uranium series dating would be needed to establish the length of Quaternary time over which gypsum and halite deposition have dominated chemical precipitation from dripwaters. Even present-day dripwater activity is difficult to assess because caves can only be reached during dry conditions, while dripwater activity is likely to be sporadic following occasional heavy rains. A considerable number of age determinations would be required to determine whether evaporite deposition is associated predominantly with glacial or interglacial climatic conditions.

If it can be shown that halite deposition extends over a considerable time period, then it would be particularly rewarding to search for further remains of cavernicolous invertebrates in halite deposits. Little is known about the length of time for which cave-adapted species have inhabited caves and the rate at which they have become physically adapted to the subterranean environment. Fossil remains of such species are not normally preserved. However, the insect and arachnid remains recovered from the dated Webbs Cave halite stalagmite indicate that halite accumulations form an excellent preservation environment for invertebrate remains as well as having some potential for radiometric dating.

Conclusions

The shallow caves of the Nullarbor Plain provide abundant erosional and depositional evidence of significantly wetter climate conditions during Middle Pleistocene time, and probably much earlier, than prevail in the region at present. The erosional evidence consists of phreatic tubes and networks of various dimensions that may hint at more rapid groundwater flow than the sluggish groundwater movement that characterises the area now.

Since significant deposition of calcium carbonate speleothems had ceased by ca. 400 ka, the possibility must be discounted that such deposition took place during the latest cold phases of the Quaternary (e.g. the last and penultimate glacial periods when greater moisture availabilty might have been expected). Instead, the geochronological evidence presented here suggests a prolonged period of aridity in the later Quaternary. Dating some of the larger halite speleothems may well reveal a much longer history of halite deposition. This possibility is also supported by the large amount of salt weathering of both bedrock and speleothems that has taken place in some of the caves that were investigated.

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Appendix 1

Sample sites and sample collection

With one exception, samples were collected in the dark zone, well away from cave entrances, to minimise problems of porous structure due to rapid evaporation and the risk of detrital contamination. Only in one cave (Koomooloobooka) was material collected in the twilight zone because of the small size of the cave and the large number of entrances. The following sites were sampled:

Webbs Cave (N-132). Longitude 127°49'4"E, latitude 31°46'14"S

A horizontal entrance from the side of a collapse doline leading to a network of passages and small chambers.

W-1: A halite stalagmite collected a short distance from a rimstone pool deposit (Fig. 5). It was 16 cm high and, subsequently, was cut into six segments to provide material for dates UEA 299 to UEA 304 (Fig. 8).

W-4: A sample of white calcite representing the 11 cm long tip of a stalagmite fragmented by salt weathering. Collected in the same chamber as W-1.

W-6: Another broken sample of white calcite 10 cm long and collected from the same chamber as W-1.

In another chamber of the cave, 10 fragments of a halite speleothem were found. They were pieced together to form a 278 cm tall stalagmite from 10–20 cm in diameter. Collapse had been caused by partial resolution. The specimen was collected on a later expedition and taken to the Australian National University where six core samples were removed for $^{230}Th/^{234}U$ dating. However, because of their extremely low uranium content it was found impossible to date these samples. The stalagmite is now in the collections of the West Australian Museum. Caldwell *et al.* (1982) have given a short description of the speleothem together with details of chemical analyses. A sample from the core was shown to consist of 95.8% halite, 3.6% chemical impurities and 1% water. Part of its interest lies in the fact that it appears to be the largest halite speleothem recorded anywhere in the world. Further details of the find are given by Barnes (1982).

Kellys Cave (N-165). Longitude 127°46'34"E, latitude 31°45'41"S

A sloping fissure entrance leads into a well-decorated low-roofed cave containing calcite, gypsum and halite speleothems. Gypsum speleothems had first been reported by Appleyard (1980). Active halite deposition was observed. There are several roof domes, with corresponding debris piles of angular limestone fragments, that appear to be largely if not entirely due to salt wedging. On the ceilings numerous bedrock flakes could be seen in a state of partial detachment intimately associated with crystalline salt.

K-2: A sample of white calcite from the base of a 22 cm tall broken stalagmite.

KE-1: A sample cut from the core of a 47 cm tall black calcite stalagmite from 7.7–12.0 cm above the base.

KC-1: A sample of black calcite taken from the tip of a 45 cm tall broken stalagmite showing two major phases of deposition (Fig. 4).

Thampanna Cave (N-206). Longitude 127°38'54", latitude 31°41'45"

The cave entrance is located in the centre of a large solution doline with a shallow valley draining into it. The entrance is a 3 m diameter shaft, that is 11 m deep and leads to the floor of a chamber from where a steeply sloping ephemeral streamway passage leads to the lowest point of the cave. A small passage to the right leads to a phreatic tube which opens out into a series of chambers where calcite pool deposits and gypsum speleothems (some active) were found.

T-1: A broken gypsum stalactite lying on the floor of the chamber.

T3: and T4: Two samples of calcite pool deposits collected from the base of a 1 m vertical section exposed by rockfall in the ceiling and walls of a low-roofed chamber. The deposit had accumulated to incorporate several stalactites while broken fragments of others were found lying horizontally within it (Fig. 2). A few gypsum speleothems have grown from the ceiling exposure of the pool deposits.

Witches Cave (N-193). Longitude 127°46'40", latitude 31°49'36"

The cave entrance is located at one side of a double doline and leads to a constricted stream passage that provides access to a single, low-roofed chamber. The cave contains a large amount of black calcite speleothem, including many columns that have been strongly fragmented by subsequent salt weathering. Much of the floor is covered by angular shards of both calcite speleothems and bedrock. No major speleothems of either gypsum or halite were observed but halite occurred abundantly in cracks and fissures.

WIT-2: Sample of light-coloured calcite from broken stalagmite.

WIT-3: Sample from central portion of flowstone layer.

Mullamullang Cave (N-37). Longitude 127°13'59"E, latitude 31°43'44"S

The cave entrance is at the base of a large collapse doline. It is a deep cave (119 m) containing a number of watertable lakes and with 13 km of mapped passage it is one of the most extensive caves of the Nullarbor karst. The zone of the oscillating watertable around the lakes is characterised by gypsum crusts. The large main passage has a series of domes with associated talus piles produced mainly by roof collapse. In places salt weathering is also a significant process of cave enlargement. Well developed tafoni, that appears to represent modification of a phreatic spongework, can be seen close to the entrance in the main passage near Smoko Junction.

A variety of types of outstanding halite speleothems including stalactites, helictites, columns, extrusion forms and wallcrusts

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are found in the Salt Cellars. This is a phreatic network of small passages that constitutes part of the Easter Extension. In common with other deep caves, carbonate speleothems are generally absent. It suggests that the deep caves either were not in existence or remained below the watertable when deposition of calcium carbonate was taking place.

M-1: At one of the talus piles, fragments of banded flowstone were found. It appears to have formed in a dilation cavity between two beds before being removed by ceiling collapse. If dilation was due to the presence of a cave below as seems likely, it means that a large cavity was already in existence when the flowstone was being deposited. Absence of other carbonate deposits from the cave suggests that it was still waterfilled. The sample was collected in the hope that dating would provide a minimum age for the development of the main passage.

Koomooloobooka Cave (N-6). Longitude 129°35'22"E, latitude 31°29'11"S

It is a shallow cave with a number of vertical entrances into a daylight chamber. Two side chambers lead from it, one of which shows evidence of once having been covered with abundant carbonate speleothems. There is a high degree of fragmentation due to salt weathering, but sufficient material remains *in situ* to show that here, as in the Mundrabilla caves, there was a phase of black calcite formation followed by a later one of light-coloured calcite.

KW-2: Sample of light-coloured calcite taken from broken stalactite fragment 11 cm long.

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Late Quaternary palaeotemperature records for two Tasmanian speleothems

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Two stalagmites from a limestone cave in the Florentine Valley, Tasmania, dated by ^{14}C and uranium series methods, provide an estimate of palaeotemperatures on the basis of $^{18}O/^{16}O$ analysis. One of the stalagmites shows continuous deposition between 98 ka and 55 ka BP at a uniform rate of 20 mm/ka. The $\delta^{18}O$ data which have a positive relationship with mean annual temperature indicate slightly higher than present day temperatures at 95 ka BP, followed by a gradual decline, culminating in a temperature minimum at about 62 ka BP. This was followed by a rapid temperature rise to a peak still below present-day temperature at about 57 ka BP.

The other stalagmite has an age range of approximately 4300–2900 years BP and an extremely rapid growth rate of 500 mm/ka. $^{18}O/^{16}O$ ratios indicate significant temperature lowering up to at least 2°C during the Late Holocene, in excellent agreement with previous palaeotemperature data from a cave site in northern Tasmania.

Key words: climatic change, ESR analysis, isotopes, palaeotemperatures, radiometric dating, speleothems.

INTRODUCTION

The aim of the study was to extend and confirm earlier palaeotemperature data from Tasmania (Goede & Hitchman 1984; Goede *et al* 1986) and to gain a better understanding of the role of temperature in Late Quaternary and Holocene environmental change. The speleothems used in this study were collected from Frankcombe Cave, developed in folded Ordovician marine limestones in the Florentine Valley, south central Tasmania (146°27′06″E, 42°31′54″S) at an altitude of 360 m above sea level (Fig. 1). The cave has a steeply declining entrance passage on the side of a small limestone hill and at a depth of 20 m this passage connects with a horizontal system of stream passages. Both speleothems were collected from small chambers some 4 m above the floor of an intermittent stream passage.

Stalagmite FC, 720 mm tall (Fig. 2), was removed from an *in situ* position and was receiving drip water from a stalactite when collected. The upper part of the second stalagmite (FT) was broken. The lower part was collected *in situ* and had grown on top of an older stalagmite (FU) characterized by a different depositional mode and smaller diameter (Fig. 2). The two stalagmites were separated by a clay-rich detrital layer which appears to record a major flood event. FU was 330 mm tall and had large voids along the longitudinal axis. FT was 907 mm tall of which the basal 860 mm recorded continuous deposition. The uppermost 47 mm has three short, separate phases of normal deposition and one phase of botryoidal 'moonmilk' formation, but did not contain sufficient material to be dated.

Except close to cave entrances, speleothem deposition usually takes place under conditions of near-constant temperature, approximately equal to the mean annual temperature at the surface. Monthly measurements in Frankcombe Cave in 1979 recorded a mean annual temperature of 8.3°C with a range of approximately 0.4°C (Goede *et al* 1982). Mean annual precipitation in the area is estimated at 1500 mm. The natural vegetation was wet sclerophyll forest which has been modified by clearfelling and burning.

THEORETICAL CONSIDERATIONS

Geochronology

Two methods of radiometric dating are available to determine the ages of speleothems. Specimens younger than 30 ka BP can be dated using ^{14}C analysis. This method provides high precision dates but has the disadvantage of overestimating radiocarbon ages by a variable amount because

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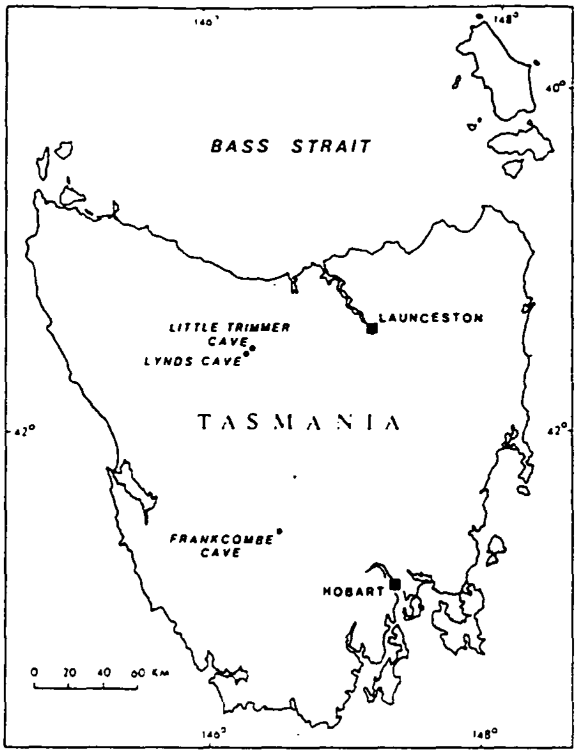

Fig. 1 Locality map showing positions of cave sites with palaeotemperature records within Tasmania.

some of the carbonate in solution is derived from carbonate rocks causing dilution of the ^{14}C concentration with old carbon (reservoir effect). Further complications arise because fractionation of carbon isotopes may occur as soon as seepage water comes into contact with the cave atmosphere. Fractionation may be due to precipitation of calcite from the solution and to isotopic exchange between the HCO_3^- in solution and CO_2 in the cave atmosphere (Hendy 1970). The reservoir effect is not constant and appears to vary between individual stalagmites. ^{14}C dates may overestimate radiocarbon ages by anywhere between 1000 and 5500 years. Goede and Hitchman (1984) gave details of a method that involved the use of electron spin resonance (ESR) analysis and enabled the reservoir effect to be estimated.

Beyond the range of ^{14}C, the uranium-series dating technique has proven to be reliable, provided (1) the speleothems have remained a closed system to gain or loss of uranium and its decay products, and (2) the speleothems are free of detrital contaminants (Gascoyne 1984; Ayliffe & Veeh 1988). Under ideal conditions, meaningful uranium series ages up to 350 ka BP can be obtained.

Palaeoclimatology

The $^{18}O/^{16}O$ ratio of speleothem calcite can be used to estimate palaeotemperatures as long as deposition has occurred under conditions of oxygen isotope equilibrium. Fractionation may occur when evaporation takes place during deposition or where there is a rapid loss of CO_2 from the solution to the cave atmosphere. Evaporation is not a problem in Tasmanian caves so long as sites close to cave entrances and in passages with strong air currents are avoided. Relative humidity is usually at or close to 100%. Two tests for deposition under oxygen isotope equilibrium conditions are discussed in detail in Goede *et al* (1986) and have been applied successfully to both stalagmites.

In this paper, δD and $\delta^{18}O$ measurements that relate to water are expressed in per mille (‰) relative to V-SMOW (Standard Mean Ocean Water). $\delta^{18}O$ and $\delta^{13}C$ values for calcite are given as ‰ relative to PDB (Peedee Belemnite). The following subscripts are used throughout: p (precipitation); w (seepage water); fl (fluid inclusion water); and c (calcite). Where conversion of $\delta^{18}O_c$ values to V-SMOW is required for palaeotemperature calculations, the relationship supplied by Friedman and O'Neil (1977) is used:

$$\delta\text{V-SMOW} = 1.03086\,\delta\text{V-PDB} + 30.86 \quad (1)$$

When oxygen isotope equilibrium conditions prevail, the values of $\delta^{18}O_c$ along the growth axis of a stalagmite are controlled by three factors discussed in detail by Harmon *et al* 1978 and Goede *et al* 1986. It has previously been demonstrated that a positive relationship exists between $\delta^{18}O_c$ values and mean annual temperature for speleothems in the Mole Creek area of northern Tasmania (Goede & Hitchman 1984; Goede *et al* 1986). A similar relationship also holds true for the two speleothems examined here.

In the present study, isotopic compositions of precipitation, cave drips and actively forming speleothems at the site are well documented (Goede *et al* 1982). Unpublished information is also available on the δD composition of precipitation and one cave drip site. Monthly samples of precipitation and cave seepage waters were collected during 1979. The weighted mean-annual isotope values for precipitation were $\delta^{18}O_p = -5.1$‰ and $\delta D_p = -30$‰. Correlation. regression analysis of the two variables yielded:

$$\delta D_p = 5.2\delta^{18}O_p + 2.7 \qquad (r^2 = 0.450) \qquad (2)$$

Student's t-test ($t = 2.9820$, d.f. $= 11$) shows the correlation to be significant ($P < 0.02$).

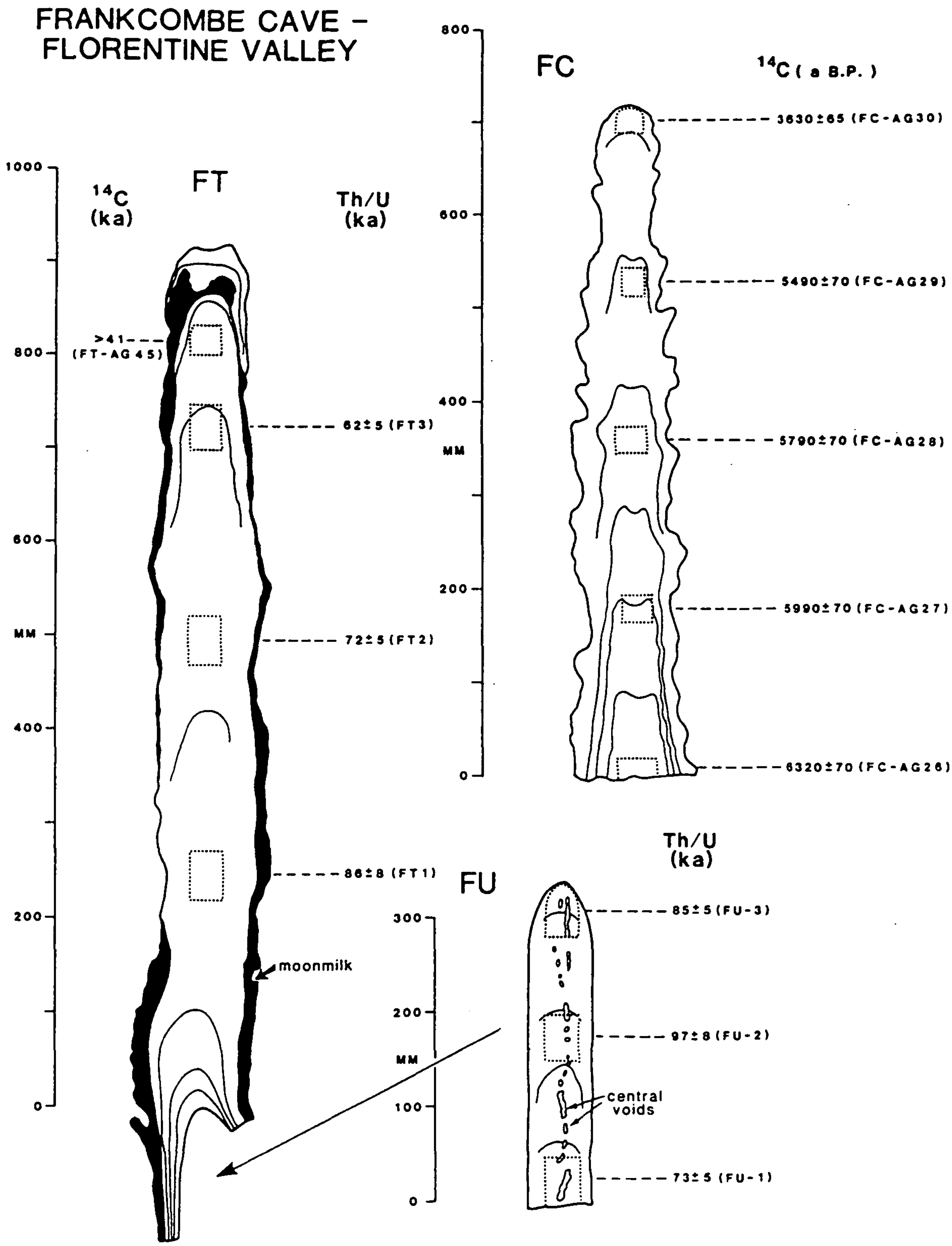

Fig. 2 Longitudinal section of FC, FT and FU stalagmites indicating nature of depositional layering and giving positions and values of all radiometric dates.

For seepage waters, monthly collections for $\delta^{18}O_w$ at two drip sites gave an annual mean value of $-5.3 \pm 0.1‰$ and similar determination of δD_w at one drip site yielded an annual average of $-26 \pm 2‰$. In order to assess the present-day oxygen isotope composition of speleothem material under equilibrium conditions, the $\delta^{18}O_c$ values of the tips of three actively forming straw stalactites were analysed. Following the procedure described in detail by Goede and Hitchman (1984), a value of $-4.0‰$ was determined. An independent estimate of this value can be made if the isotopic composition of the seepage water and the cave temperature (8.3°C) are known. It has previously been shown that in the Tasmanian cave environment deposition takes place predominantly during the winter months (Goede & Hitchman 1984) so that the most appropriate value to use for seepage water is the weighted mean of winter precipitation ($\delta^{18}O_w = -5.7 \pm 0.1$).

The equation used to estimate $\delta^{18}O_c$ was originally determined by O'Neil *et al* (1969) with an adjustment for CO_2 equilibration change by Friedman and O'Neil (1977) giving:

$$10^3 \ln \alpha_{c-w} = 2.78 \times 10^6 T_A^{-2} - 2.89 \qquad (3)$$

where $\alpha_{c-w} = (^{18}O/^{16}O)_c/(^{18}O/^{16}O)_w$ and T_A is the cave temperature expressed in Kelvins. The $\delta^{18}O_c$ value obtained is converted to ‰ V-PDB using equation (1). The value obtained is $-3.9 \pm 0.1‰$, in excellent agreement with the value of $-4.1‰$ estimated from the analysis of actively forming straw stalactites. The value of $-4.0‰$ has therefore been adopted as a good estimate of the isotopic composition of modern speleothem calcite in Frankcombe Cave.

METHODS AND INSTRUMENTATION

Radiocarbon age determinations were carried out by conventional methods. Corrections for the reservoir effect involved ESR analysis of the speleothems as discussed in detail by Goede and Hitchman (1984). For ESR analysis, samples were drilled along the core in longitudinal section at 20 mm intervals using a 5 mm diameter drill. The signal normally used for ESR dating of calcite at $g = 2.0008$ (h_3) was absent from all samples, but ESR spectra showed a peak at $g = 2.006$, sometimes referred to as h_1 (Smith *et al* 1985), which could be used for analysis. Exposure of samples to incremental gamma irradiation from a ^{60}Co source produced a linear response in peak intensity to radiation dose. The samples were analysed on a JOEL JES-FE 3X ESR spectrometer using ambient temperatures at 100 kHz with a magnetic field modulation of 10^{-4} T, a microwave power of 1 mW and an amplitude of 2.5×1000. For each sample the intensity of the h_1 peak was recorded as the mean of five measurements.

For uranium series analysis a $^{228}Th/^{232}U$ spike, calibrated and distributed by the Uranium Series Intercalibration Program (Ivanovich & Warchal 1981) was used throughout. The instrumentation consisted of a Nuclear Data Model ND 2400 pulse-height analyser with ORTEC surface barrier detectors.

For stable-isotope analysis, samples were obtained in the same manner as for ESR. Both FC and FT stalagmites were sampled at 20 mm intervals but due to their contrasting rates of growth, sample spacing represents very different time intervals, approximately 40 years for FC and 1000 years for FT. CO_2 was prepared from the samples by reacting them in a vacuum with anhydrous H_3PO_4 and the samples were purified using a conventional glass extraction line. Both $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios were determined with a VG Micromass 602D stable-isotope mass spectrometer; analytical precision was $\pm 0.1‰$ determined during runs. To determine whether deposition had taken place under conditions of isotope equilibrium, three sets of seven 2 mm samples each were drilled from each of three growth layers from the two stalagmites. The results of analyses confirmed deposition under conditions of isotopic equilibrium.

Hydrogen isotope determinations of fluid inclusions (δD_{fi}) required much larger samples, and 5 mm thick slices were cut from the core of FC at stratigraphic positions equivalent to those sampled for $\delta^{18}O_c$ and $\delta^{13}C_c$ analysis and the same instrument used for isotopic analysis. Water was extracted using the decrepitation technique developed by Yonge (1981, 1982). While it has the advantage of requiring relatively small size samples for analysis, both Yonge (1982) and Goede *et al* (1986) have found independently that the method produces D_{fi} values that are consistently isotopically light by approximately 20‰. Water samples were reduced to hydrogen using the technique of zinc reduction in a sealed tube as proposed by Coleman *et al* (1982) with subsequent improvements by Kendall and Coplen (1985).

The technique has an analytical precision of $\pm 2‰$ for water samples. Because at least 4 g of calcite was required to extract a sufficient quantity of water it was possible to repeat analyses once in some but not all samples. Poor reproducibility ($\pm 5‰$) is believed to be due to the inhomogeneity of fluid inclusion water within the sample. Because of this problem and also because of the complexity and time-consuming nature of the extraction procedure, D_n values were determined only for the FC stalagmite. Results have been adjusted by 20‰ for systematic error, which represents an average value, so individual determinations may be in error by more than 5‰.

RESULTS

Radiocarbon ages

The ^{14}C ages obtained are given in Table 1. A plot of the apparent ages of the five FC samples vs their median position above the stalagmite base forms a linear plot for the four older samples, indicating an approximately uniform rate of growth for the stalagmite. However, the youngest date is aberrant and may be due to a reduced rate of growth towards the top or enrichment in ^{14}C due to nuclear weapons testing. The ESR analyses do not support the first suggestion, whereas the second is a distinct possibility as the stalagmite was receiving drip water before removal from the cave.

ESR analysis

On a plot of ESR peak intensity (Ih_1) against height above the base (H) of the FC stalagmite, there is a long-term linear age-related trend, despite obvious shorter term cyclical variations which may be due either to variations in the concentration of radioactive elements or to changes in the sensitivity of different layers to gamma irradiation (Fig. 3). Sensitivity changes may be related to variations in either organic or inorganic trace impurities in the stratigraphic sequence of calcite deposition (Goede 1989). Even the youngest samples display an ESR spectrum with an h_1 peak intensity that can be readily measured above the background 'noise'

Table 1 ^{14}C age determinations of FC and FT stalagmite samples from Frankcombe Cave.

Sample No.	Laboratory No.	Medium height above base (mm)	Apparent ^{14}C age (years BP)	Estimated calendar age (years BP)
FC-AG26	Pta-2499	10	6320 ± 70	4365
FC-AG27	Pta-2571	180	5990 ± 70	3910
FC-AG28	Pta-2574	360	5790 ± 70	3680
FC-AG29	Pta-2575	530	5490 ± 70	3295
FC-AG30	Pta-2505	710	3630 ± 65	—
FT-AG45	SUA-2208	815	> 41 000	—

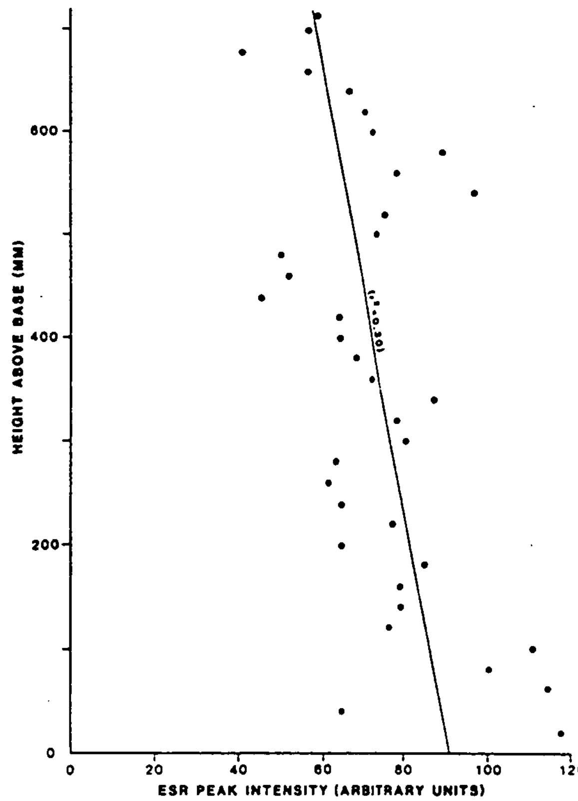

Fig. 3 Relationship between height (H) in mm above the base of the speleothem FC and ESR peak intensity (Ih_1) with regression line. Although the correlation is statistically significant there are clearly cyclical variations in Ih that are not related to the age of individual samples.

produced when samples are analysed at ambient temperatures. Until calcite samples are >1000–2000 years old the signal cannot be identified, and hence it is concluded that no significant deposition has taken place during the last 2000 years or more, despite observations that the stalagmite was receiving drip water when collected.

Correlation, regression analysis of the relationship between height above base (H) of the stalagmite and peak intensity (Ih_1) gave the following relationship:

$$Ih_1 = 91.2192 - 0.4709H \quad (r^2 = -0.30) \quad (4)$$

Student's t-test ($t = 3.8022$, d.f. $= 34$) indicates a highly significant ($P < 0.001$) correlation. The relationship can be used to estimate the age ratio in calendar years between any two of the ^{14}C dates for which the median position along the stalagmite axis is known (Goede & Hitchman 1984). The age ratio in calendar years between samples Pta-2499 and Pta-2575 is estimated to be 0.73. The ^{14}C reservoir effect is assumed to be x years. Values for x are taken at intervals of 500 years over the range 1000–5500. For each value of x the two selected dates are converted to calendar years using the calibration tables of Klein *et al* (1982) and the apparent age ratio between the two dates calculated. The ratio matching the value of 0.73 is established by interpolating between 500 year intervals and the reservoir correction estimated as 2400 years. This is remarkably close to the reservoir effect of 2160 years for a stalagmite from Lynds Cave, Mole Creek, in northern Tasmania (Goede & Hitchman 1984). Since Fig. 3 indicates that the whole of FC grew at a uniform rate, correlation regression analysis of height above base against the four calendar age estimates is used to provide a timescale for the FC stalagmite. Thus, the stalagmite formed between approximately 4300 years and 2900 years BP at an extremely rapid rate of approximately 500 mm/ka. In contrast, the FU and FT stalagmites could not be dated by ^{14}C because they were too old. A ^{14}C date close to the upper limit of the main depositional phase of FT yielded an age of >41 000 years BP (SUA-2208) (Table 1; Fig. 2).

Uranium series ages

The uranium series disequilibrium dating technique was used to determine the ages of three samples from each of the two stalagmites FT and FU (Table 2). The three samples of FT have a clear progression of ages in stratigraphic order. A plot of radiometric ages against median sample height above base indicates a linear growth rate of about 20 mm/ka over the period 98–55 ka BP (Fig. 4). The implied cessation of growth at about 55 ka is further constrained by the ^{14}C age limit of >41 ka obtained from the uppermost layers of the main growth phase. On the assumption of uniform growth throughout this interval, a time scale is provided for temporal variations of $^{18}O_c$ and $^{13}C_c$ values at this site (see Fig. 6).

In contrast, the age determinations for FU are inconclusive, with at least one out of stratigraphic sequence. As well, the age determination for FU-3 appears young with respect to the age sequence in FT, in particular when it is considered that the detrital clay layer separating FU from FT may represent a major hiatus. If the ages in FT are accepted as correct, the age of FU-1, and possibly FU-3, must be too young. A likely explanation for the anomalous ages is secondary addition of uranium. In view of the low concentration levels of uranium in these stalagmites, the amount of secondary uranium required to produce a measurable decrease in the $^{230}Th/^{234}U$ ratio (and hence age) would be minimal. The uranium concentrations in samples from FU are all significantly higher than those in FT. If this difference in uranium concentration between the two stalagmites is caused by the post-depositional addition of uranium to FU at a late stage, the effect on its $^{230}Th/^{234}U$ ages could be substantial. The most likely time for any infiltration of the lower stalagmite with secondary uranium would have been during a flood, when the lower stalagmite was temporarily submerged, as indicated by the layer of detrital clay separating the two stalagmites. Such infiltration would have been greatly facilitated by the highly porous nature of the lower stalagmite.

Samples FU-2 and FU-3 have somewhat lower $^{234}U/^{238}U$ ratios than the other samples. The same samples also have much lower $^{230}Th/^{232}Th$ ratios, indicating contamination with detrital material, such as clay or silt, from external sources. The detrital components may also contain uranium, normally with $^{234}U/^{238}U$ ratios close to or even less than 1.00. The net effect of detrital contaminants containing both thorium and uranium on the $^{230}Th/^{234}U$ ratios is difficult to evaluate without additional information, but it may explain why samples FU-2 and FU-3 have ages which are less offset from their 'expected' values than FU-1, in spite of their higher total uranium concentrations.

Table 2 Uranium series data and radiometric ages of FT and FU stalagmites.

Sample No.	Uranium (parts/10^6)	$^{234}U/^{238}U$*	$^{230}Th/^{232}Th$*	$^{230}Th/^{234}U$*	Age (ka BP)	Height above base (mm)
FT-3	0.026	1.23 ± 0.04	76	0.44 ± 0.02	62 ± 5	724
FT-2	0.038	1.21 ± 0.03	>1000	0.49 ± 0.02	72 ± 5	496
FT-1	0.041	1.22 ± 0.05	>800	0.56 ± 0.03	86 ± 8	246
FU-3	0.075	1.17 ± 0.04	16	0.55 ± 0.02	85 ± 5	308
FU-2	0.098	1.12 ± 0.04	28	0.60 ± 0.03	97 ± 8	175
FU-1	0.062	1.28 ± 0.05	>1000	0.50 ± 0.02	73 ± 5	25

*Activity ratios.
Errors shown are based on counting statistics (± 1σ).

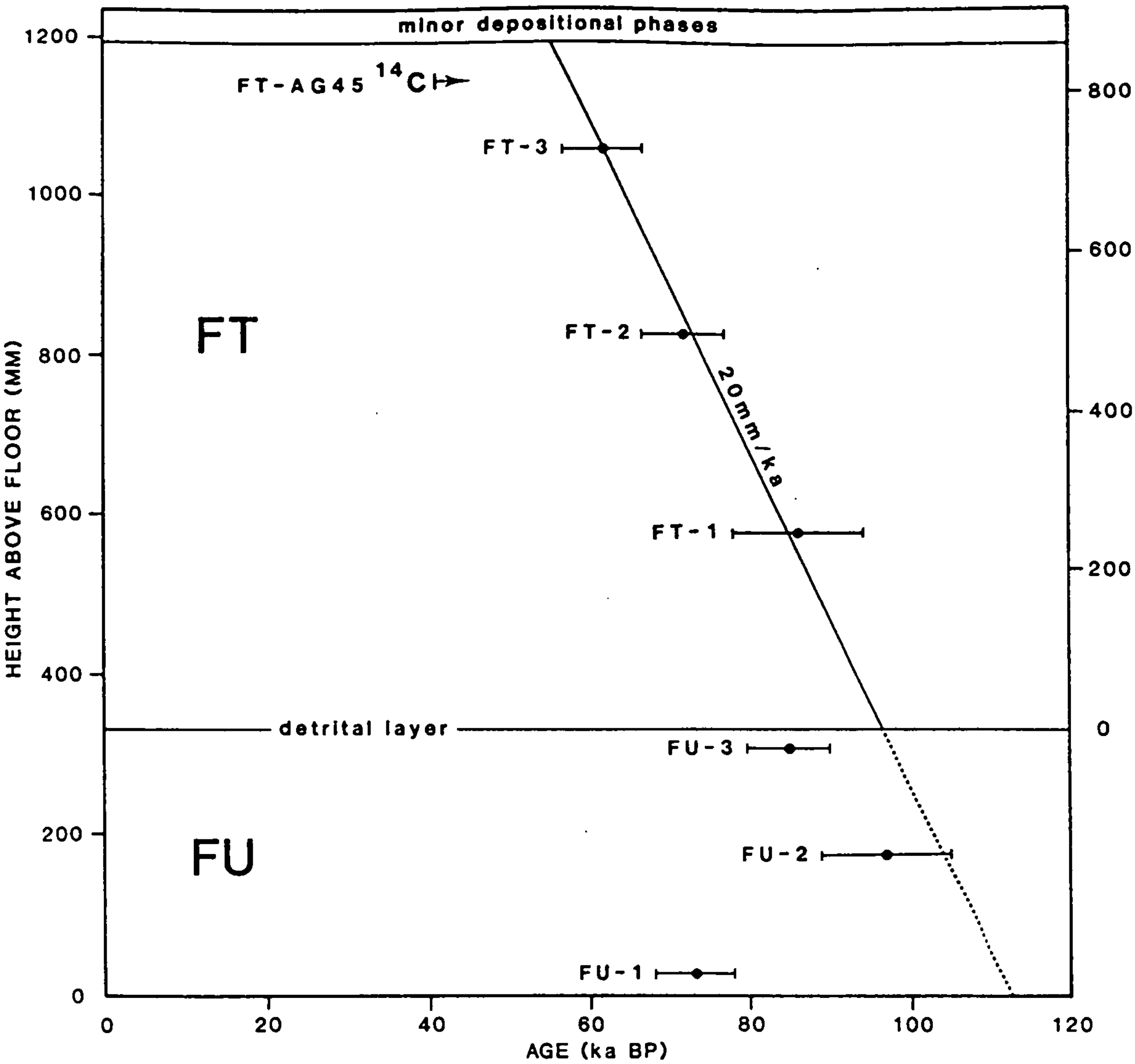

Fig. 4 Radiometric ages of samples from stalagmites FU and FT plotted as a function of their position of deposition. The regression line that defines the growth rate for the upper stalagmite has been extended into the lower stalagmite to show an 'age offset' in the lower stalagmite, probably caused by its infiltration with secondary uranium during a flooding event represented by the layer of detrital clay (see text). The layer of botryoidal 'moonmilk' near the top of FT suggests a change in environmental conditions after the major growth phase terminated at about 55 ka BP.

Because the assumption of a closed system is clearly invalid for stalagmite FU, its uranium series ages should be regarded with caution and treated as minimum ages.

To assess the possibility that the isotopic composition of uranium in the cave water may have changed over time, a sample of modern dripwater was collected from within 3 m of the site where the FT and FU stalagmites were collected. This water had a uranium concentration of 0.176 μg/L and a $^{234}U/^{238}U$ ratio of 1.14 ± 0.05. Thus, the water from which the two stalagmites were derived, corrected for age, had a significantly higher $^{234}U/^{238}U$ ratio than that of modern dripwater. Temporal changes of this ratio in cave seepage waters have been documented elsewhere (Thompson *et al* 1975) and are the reason why $^{234}U/^{238}U$ ratios alone cannot be used for reliable age determination of speleothems.

Stable isotopes

The results of stable-isotope analyses are given in Figs 5 and 6. Stalagmite FU was not used for

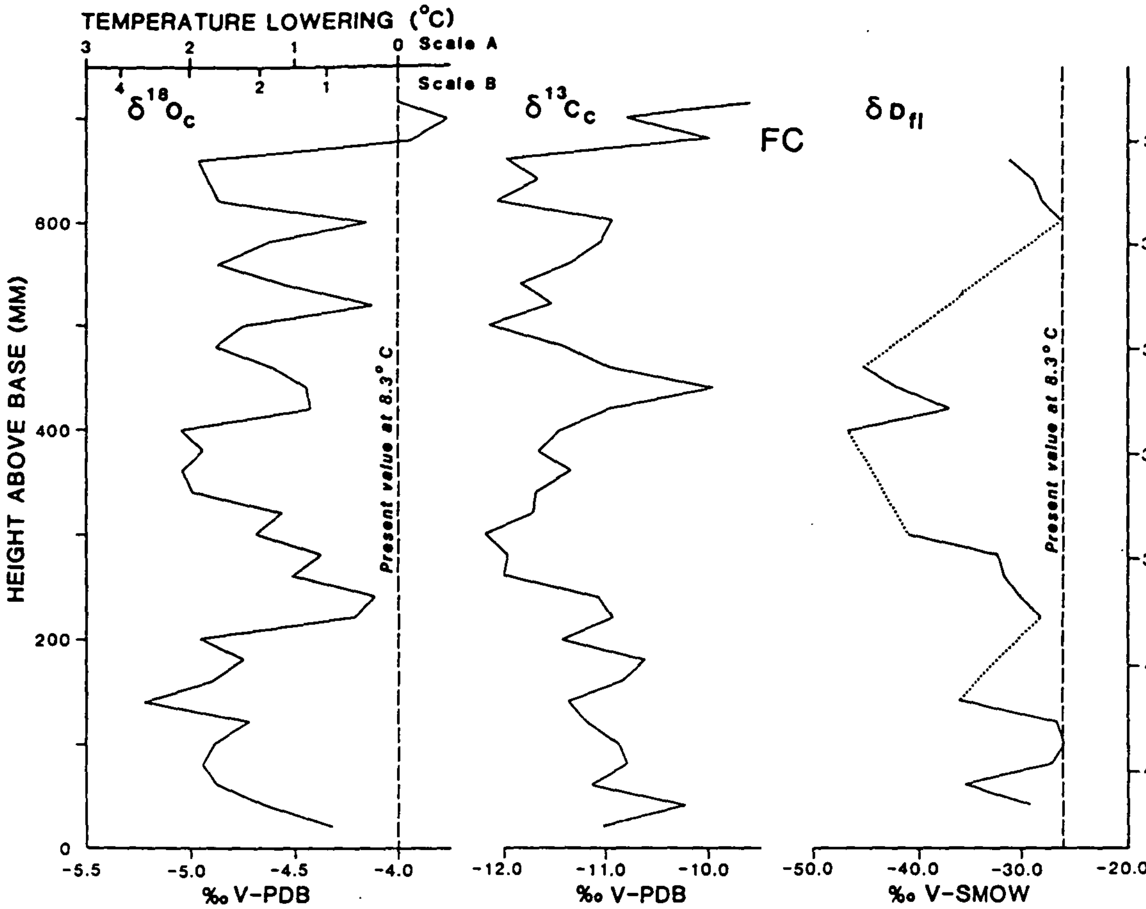

Fig. 5 Temporal variations in the values of $\delta^{18}O_c$, $\delta^{13}C_c$ and δD_{fi} measured at intervals along the longitudinal axis of the FC stalagmite. Present-day values of $\delta^{18}O_c$ and δD_w for Frankcombe Cave are indicated. Scales of temperature lowering (A and B) indicate minimum and maximum values.

palaeotemperature studies because of its highly porous nature and questionable uranium series dates. The lack of correlation of $\delta^{18}O_c$ values with $\delta^{13}C_c$ results indicates that FC and FT have been deposited under conditions of oxygen isotope equilibrium. For FC, correlation yields $r=-0.19$ ($n=36$), and for FT it gives $r=0.03$ ($n=42$); multiple analyses along three individual growth layers confirmed the absence of significant evaporative effects.

Stalagmite FT is unusual in that low $\delta^{18}O_c$ values are associated with surprisingly high $\delta^{13}C_c$ values, the highest being -1.65‰. Values for $\delta^{13}C_c$ in Tasmanian stalagmites deposited under conditions of oxygen and carbon isotope equilibrium are usually > -8‰, because of the biogenic contribution of CO_2 to the seepage water as it passes through the soil. Isotopic fractionation cannot be responsible for the high $\delta^{13}C_c$ values in FT, as indicated by the lack of significant correlation with $\delta^{18}O_c$ values. The results imply that FT, as well as FC, can be considered suitable for palaeotemperature analysis.

Fig. 5 indicates that D_{fi} values for the FC stalagmite are generally isotopically lighter than the annual average of present-day seepage ($\delta D_w = -26$‰). Cave seepage waters of humid temperate environments have been shown to have D/H and $^{18}O/^{16}O$ ratios similar to those of the weighted mean annual precipitation of the locality (Goede *et al* 1982; Yonge *et al* 1985). The same isotope ratios in mean annual precipitation are in turn a function of mean annual temperature (Siegenthaler 1979). The D_{fi} values indicate clearly

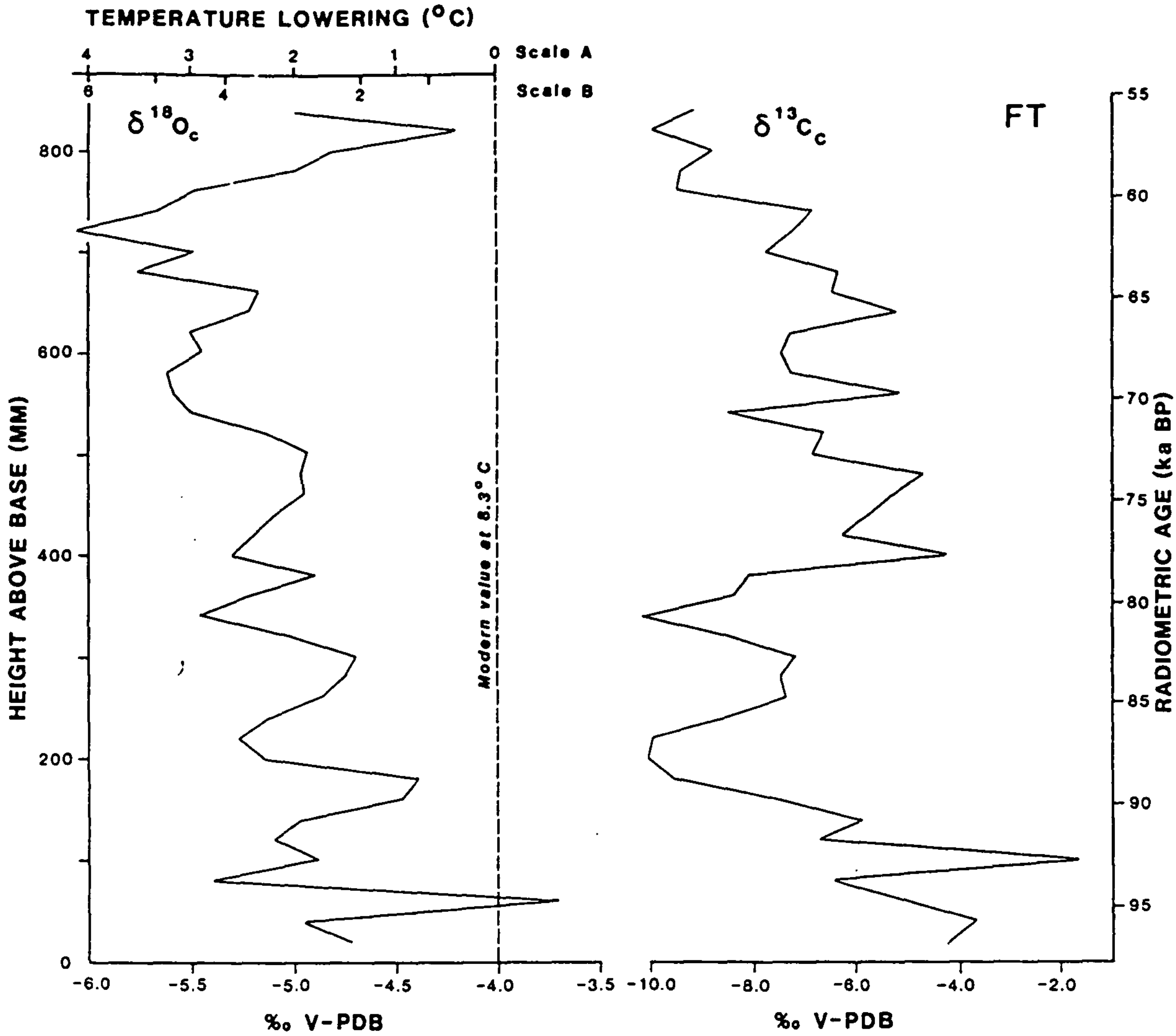

Fig. 6 Temporal variations in the values of $\delta^{18}O_c$ and $\delta^{13}C_c$ measured at intervals along the longitudinal axis of the FT stalagmite. The modern value of $\delta^{18}O_c$ for Frankcombe Cave is shown. Note the minimum values of $\delta^{18}O_c$ at about 62 ka BP, indicating very cold conditions.

that mean annual temperatures over the period when FC was being deposited were generally lower than they are at present. $\delta^{18}O_c$ values, except those of the youngest three samples, are also consistently lower than those expected from present day equilibrium deposition ($\delta^{18}O_c = -4.0‰$). This indicates that $\delta^{18}O_c$ values have a positive relationship with mean annual temperature whereas most stalagmites exhibit a negative relationship between the two variables. However, a positive relationship also exists in stalagmites from caves at Mole Creek in northern Tasmania (Goede *et al* 1986) and the probable reasons have been discussed therein. A positive relationship is also known for stalagmites from Vancouver Island, Canada (Gascoyne *et al* 1981).

The FT stalagmite (Fig. 6) also gives $\delta^{18}O_c$ values below the $-4.0‰$ value expected under present-day conditions, with only one exception. A maximum value of $-3.7‰$ was observed shortly after deposition commenced at about 95 ka BP and was followed by a downward trend until a minimum of $-6.0‰$ was reached at about 62 ka BP. A rapid rise in values then took place until a maximum of

$-4.2‰$ was reached at about 57 ka BP. The most notable feature of the $\delta^{13}C_c$ record is the extremely wide range of values, from $-10.1‰$ to $-1.7‰$.

PALAEOTEMPERATURE ESTIMATES

In an earlier paper, Goede *et al* (1986) established a highly significant positive correlation between $\delta^{18}O_c$ and δD_{fl} in a stalagmite from Little Trimmer Cave, at Mole Creek in northern Tasmania. This relationship was used to estimate values for $\delta^{18}O_{fl}$ at stratigraphic positions where $\delta^{18}O_c$ values were also known, and at Mole Creek the local relationship between δD_p and $\delta^{18}O_p$ values was also used to determine palaeotemperatures. These procedures cannot be followed here, firstly because of the poor correlation between monthly values of δD_p and $\delta^{18}O_p$ (equation 2), and secondly because there is no statistically significant correlation between values of δD_{fl} and $\delta^{18}O_c$ ($r=0.21$, $n=19$). The latter is probably due to the fact that during most of its depositional phase FC had a splashcup (Fig. 2), creating an irregular depositional surface.

If independent estimates can be made of the amount of temperature lowering at the time of the early last glacial maximum, as observed in the isotope record of the FT stalagmite (Fig. 6), then the record can be calibrated in terms of temperature change. Unfortunately, the early last glacial maximum is outside the range of ^{14}C dating and hence is difficult to positively identify in the terrestrial stratigraphy of Tasmania. It is probably represented in basal pollen zone 10 in the pollen diagram of Pulbeena Swamp (northwestern Tasmania), a sequence of freshwater marl and swamp-peat deposits (Colhoun *et al* 1982). The pollen content of zone 10 has striking similarities to zone 2 in the same core. Zone 2 represents the late last glacial maximum, dated between 25 ka and 15 ka BP.

In deep-sea cores (Hays *et al* 1976), the early last glacial maximum (marine isotope stage 4) is represented by slightly heavier values of $\delta^{18}O_c$ in planktonic forams than the late glacial maximum (marine isotope stage 2). This indicates that glacial ice volumes world-wide were marginally smaller during marine isotope stage 4 than they were during marine isotope stage 2.

In Antarctica, the early and late last glacial maxima are represented by isotope zones D and B, respectively. Differences in $\delta^{18}O$ and δD values of ice are minor, when the two glacial maxima are compared (Lorius *et al* 1985; Jouzel *et al* 1987), suggesting that similar temperatures prevailed during both glacial maxima.

In Tasmania, Colhoun (1985, p. 47) has found that 'the Margaret Glaciation (the last glaciation) ice limits correspond with the maximum phase of the last glaciation and date to 20 000–18 000 years BP'. However Fitzsimons (1988) recognized glacial deposits (Chamouni Formation) in the King River valley in western Tasmania beyond the late last glacial ice limit and believed the deposits to belong to the Margaret glacial phase but beyond the range of ^{14}C dating (>48.7 ka BP). His evidence suggests that, locally at least, a more extensive ice cover existed than during the late last glacial Margaret advance. This evidence and isotopic data from deep sea cores and Antarctic ice cores all indicate that temperatures at the early last glacial maximum were at best only marginally warmer than at the late last glacial maximum, so that estimates of temperature lowering in Tasmania during the latter can be used as an indication of temperature lowering during the former.

Colhoun (1985) compared the altitudes of equilibrium lines of ice masses existing during the late last glacial maximum, with the estimated height of the modern snowline and computed a mean annual temperature lowering of 6.5°C for the West Coast Range. Gibson *et al* (1987) record a macrofossil of the alpine bolster plant *Donatia novae-zelandia*, with a ^{14}C age of 21 180 ± 370 years BP, approximately 230 m above sea level in the King River Valley. The date is close to the last glacial maximum and the authors imply a minimum temperature depression of 4.5°C. Given that the early last glacial maximum was at best only marginally warmer, a 4° to 6°C range of temperature lowering for this event would be a good estimate.

As indicated in Fig. 6, a 4–6°C temperature lowering corresponds to a 2‰ lowering of $\delta^{18}O_c$ values, that is between 0.50‰ and 0.33‰ per °C. Two scales of temperature lowering (A and B) are given in Figs 5 and 6 and represent the likely maximum and minimum limits for corresponding isotopic values. The lowest value of $\delta^{18}O_c$ for FT is $-6.0‰$ at about 62 ka BP, the early last glacial maximum. The highest value, of $-3.8‰$, occurred at about 95 ka BP and represents a mean annual temperature marginally higher than today.

The short Holocene record of FC extends from 4300 to 2900 years BP. Mean annual temperatures appear to have been significantly lower than today, reaching a minimum 2° to 3°C lower at about 4100 years BP. Temperatures were nearly as low on at least four other occasions between 3800 and 3000 years BP.

DISCUSSION

The FT palaeotemperature record overlaps in time (98 to 75 ka BP) with that of the LT stalagmite from Mole Creek (Goede *et al* 1986). Because of the nature of the sampling, close comparisons cannot be made. Both FT and LT have relatively slow growth rates and time intervals between adjacent samples are of the order of 1000 years. Both records show temperatures significantly below those of the present day for at least 95% of the time. Whereas FT has a temperature peak at 95 ka BP, LT has peaks at 89 ka BP and 76 ka BP. Considering the limitations of dating, the older temperature peak in LT may well correspond with that in FT, but there is no equivalent for the younger temperature maximum.

The FC record provides clear confirmation of part of a much longer palaeotemperature record obtained from a stalagmite (LY) from Lynds Cave at Mole Creek, northern Tasmania (Goede & Hitchman 1984). The uppermost part of the LY sequence covers the same time period as FC but was sampled at longer time intervals (250 years). It also indicates temperatures significantly below the present over the same time period, with conditions of maximum cold at about 3800 years BP. The difference in age between the FC and LY minimum temperature peaks is not significant and the peaks probably refer to the same event.

The unusually high $\delta^{13}C_c$ values obtained in parts of the FT stalagmite cannot be explained by isotopic fractionation. Dreybrodt (1982) argued that calcite speleothems can be deposited in the absence of isotopically light (−27 to −13‰) biogenic carbon dioxide derived from soils where caves are overlain by glaciers or bare karst surfaces. He quoted $\delta^{13}C_c$ values from +6‰ to +10‰ found by Geyh and others (unpubl. data) from speleothems in caves of the Dachstein Massif, in Austria. Such results are beyond the maximum value obtained by fractionation during deposition, for which Dreybrodt (1982) claimed a maximum value of +2‰. In the absence of biogenic CO_2, deposition takes place due to warming of percolating water. In winter and spring, water from melting snow becomes saturated with bicarbonate close to the ground surface. After passing through the vadose zone, water enters the cave, in which air temperatures are significantly above freezing point; the solution becomes supersaturated and deposition takes place. The high values of $\delta^{13}C_c$ in the FT stalagmite may indicate that some deposition of calcite took place in this manner, possibly explaining the low growth rate. Elsewhere it has been demonstrated that the rate of speleothem formation can be greatly reduced or even terminated during glacial periods, due to a variety of factors such as frozen ground, greater aridity and reduced CO_2 production in the soil above the cave (Gascoyne *et al* 1981; Ayliffe & Veeh 1988; Gordon *et al* 1989).

CONCLUSIONS

(i) The $^{18}O/^{16}O$ ratios of Tasmanian speleothem calcite have a positive relationship to mean annual temperature, a relationship also demonstrated from Vancouver Island (Gascoyne *et al* 1981). Mean annual $\delta^{18}O_p$ values of precipitation are determined partly by temperature conditions prevailing in the source area where evaporation takes place and partly by temperature conditions where condensation takes place prior to precipitation (Siegenthaler 1979). Both Tasmania and Vancouver Island have temperate, maritime, west coast climatic environments dominated by westerly air circulation. At present both areas receive most of their rainfall from tropical source areas due to a marked meridional component in the westerly circulation pattern. A likely explanation for the positive relationship between $\delta^{18}O_c$ and temperature is that in these areas there was an unusually large negative change in $\delta^{18}O_p$ under glacial conditions, because of a much stronger latitudinal airflow component causing a dramatic poleward shift in the moisture source areas.

(ii) The FT stalagmite record demonstrates an early last glacial minimum at about 62 ka BP with a 4° to 6°C lowering of mean annual temperature, followed by a relatively warm period with temperatures only slightly below those of the present day at about 57 ka BP.

(iii) The FC record confirms previous isotopic evidence from Lynds Cave, at Mole Creek, northern Tasmania (Goede & Hitchman 1984), which suggested that mean annual temperatures were significantly lower (2° to 3°C) in the later part of the Holocene, with a temperature minimum occurring at about 4000 years BP. While the suggestion of cooler conditions at this time is not new, most Australian evidence of temperature change based on geomorphological and palynological evidence is equivocal because of possible anthropogenic influences on geomorphic processes and vegetation dynamics. Such evidence also fails to distinguish the effects of temperature changes from those of precipitation.

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THE STRATIGRAPHIC COLUMN

LAST INTERGLACIAL COASTAL SEDIMENTS AT MARY ANN BAY, TASMANIA, AND THEIR NEOTECTONIC SIGNIFICANCE

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Introduction

Emergent, richly fossiliferous, unconsolidated quartz sands of last interglacial age occur extensively around the Tasmanian coastline (Gill & Banks, 1956; Jennings, 1959; van de Geer et al., 1979; Bowden & Colhoun, 1984; Murray-Wallace & Goede, in press) and provide critical evidence for late Quaternary neotectonism and sea level change. This note summarises the general sedimentologic and geomorphologic characteristics of the emergent coastal facies at Mary Ann Bay (Figure 1) with reference to their neotectonic significance. A brief summary of the dating methods applied to this sequence is also presented. It is hoped that this note will stimulate other workers to document important Quaternary reference sections for *Quaternary Australasia*.

Background

Evidence for Quaternary sea level change is provided by a range of coastal landforms and stratigraphic sequences in Tasmania that include narrow marine benches, elevated river terraces and sea caves and intertidal and subtidal sediments at high elevations. Richly fossiliferous coastal sediments typically occur between 11 and 32m above High Water Mark, and several examples represent the most elevated occurrences of last interglacial coastlal strata on the Australian continent. Their elevated positions in the landscape, relative ages and neotectonic significance, although anticipated by some (van de Geer et al., 1979; Bowden & Colhoun, 1984) have remained problematic in detail. Early investigators did not recognise that these features had been uplifted because Quaternary glacio-eustatic sea level curves of global applicability had not been elucidated (Gill & Banks, 1956; Jennings, 1959, 1961; Davies, 1959, 1961; Chick, 1971). Problems of interpretation were compounded by the practice of correlating the elevation of coastal strata with the tectonically overprinted Mediterranean sea-level record (e.g., references in Jennings, 1959).

Geomorphologic, lithostratigraphic and indirect palynologic evidence and radiocarbon dating, indicated that the ages of many of these coastal sequences exceeded the practical limits of conventional radiocarbon dating (ca. 45,000 years). The timing of these sea level high stands remained poorly understood however, as available dating techniques were not applicable to specific mineralogical components of sediments and many of the methods assumptions were not upheld in their stratigraphic context.

Middle Pleistocene to Holocene glacio-eustatic sea level curves of global applicability (Bloom et al., 1974; Chappell, 1974, 1983; Chappell & Shackleton, 1986) provide a framework to assess the ages of the Tasmanian coastal sequences. With reference to established models of late Quaternary sea level change, previous studies (van de Geer et al., 1979; Bowden & Colhoun, 1984) ascribed a last interglacial age (oxygen isotope substage 5e) to many of the Tasmanian coastal features based on inference and without directly dating the deposits. The anomalously high elevation of these coastal sequences compared with similar sediments of equivalent age on the Australian mainland suggests they are tectonically uplifted.

Site Description

The Mary Ann Bay sequence is exposed within an actively eroding cliff and comprises well bedded shallow water, middle shoreface sediments (Grid Reference 322417: Sheet 8312, First Edition) (Photo 1, Figure 1). The sequence attains a maximum thickness of 9.6m and unconformably overlies Jurassic dolerite. Whole *Pecten meridionalis* and fragments of *Fulvia tenuicostata* occur within laterally persistent, tabular cross-stratified, clean, medium to fine-grained quartz sands (Photos 2 & 3). Several cosets of tabular cross-stratification with numerous fining upward units occur within the sequence. The base of each coset is defined by coarse shell fragments and disarticulated *Pecten* spp., that grade into more finely comminuted shells and terminates in medium to fine grained quartz sands with a smaller component of comminuted shell (i.e., long axes 2-3mm).

The shell rich sediments are overlain by dull brown (7.5 YR 5/3) to brownish black (10 YR2/3) pedogenically modified aeolian sands of variable thickness (0.5-1m). The top of the sub-tidal coastal facies is an erosional contact and occurs some 24.5m above present HWM. The cliff exposure is terraced with an irregular bench that trends seawards and defines the contact between the Jurassic dolerite and the overlying Quaternary sequence (Figure 2).

Dating

Amino acid racemisation, electron spin resonance and radiocarbon dating methods were applied to specimens of *Pecten meridionalis* and *Fulvia tenuicostata* from the shell-rich sands at Mary Ann Bay.

Radiocarbon dating was undertaken on 5 whole, very well preserved, disarticulated valves of *Pecten meridionalis* from Mary Ann Bay. In view of the difficulties of applying uranium-series disequilibrium to the dating of fossil molluscs, radiocarbon dating was undertaken to indirectly validate the results from amino acid racemisation and electron spin resonance. The radiocarbon age of 39, 900+820/-720 (SUA-2925) indicates that the mollusca are beyond the practical limits of radiocarbon dating, but minor contamination (ca. <1%)) by modern carbon has resulted in the apparent age reported. The apparent age also points to the mobility of carbon in the environment, the relative ease with which it is assimilated by shells during lengthy diagenetic histories and the difficulty of isolating the contaminated fraction for shell dates (a problem most marked for Pleistocene materials close to the practical limits of radiocarbon dating).

Amino acid racemisation and electron spin resonance data for the Pleistocene taxa are also compared with a representative radiocarbon calibrated Holocene sequence at Ralphs Bay, near Hobart. Thes data provide an additional basis for calibration of the amino acid racemisation and electron spin resonance techniques. The extent of racemisation for a range of amino acids in specimens of *Fulvia tenuicostata* and *Pecten meridionalis* indicate a last interglacial age (oxygen isotope substage 5e: 125,000 years BP) for the sequence at Mary Ann Bay. Racemisation kinetic model ages are in accord with the timing of oxygen isotope substage 5e. These strata have been correlated by aminostratigraphy with shelly sands on the NW coast of Tasmania. The lower extent of racemisation in the Pleistocene mollusca from Mary Ann Bay, than evident for materials of the same age from more northerly sites in southern Australia is a function of their lower diagenetic temperature history (Murray-Wallace et al., 1991). A higher extent of racemisation than recorded for the Pleistocene taxa would otherwise indicate a middle Pleistocene age (cf., Murray-Wallace et al., 1988).

A similar partitioning of results for the Pleistocene and Holocene taxa based on the extent of racemisation of a range of amino acids is also evident for the electron spin resonance data (Table 1). These data provide the first direct evidence for the last interglacial age of the strata at Mary Ann Bay.

Significance

With the exception of coastal sequences attributed last interglacial ages on inference and subjective morphostratigraphic evidence (eg., Stumpys Bay site in NE Tasmania of Bowden & Colhoun, 1984), the Mary Ann Bay sequence represents the most elevated occurrence of confirmed last interglacial coastal strata on the Australian continent.

Excluding tectonically uplifted sites, Murray-Wallace & Belperio (1990) found that the height attained by the last interglacial sea surface around the Australian coastline was consistently below the 6 m reference level commonly cited. Confirmation of the last interglacial age for the sequence at Mary Ann Bay, and emergent coastal sequences in northwestern Tasmania (Muray-Wallace & Goede, in press) therefore strengthens the notion that they have been uplifted. Assuming a constant uplift rate and a +4 m level for the last interglacial sea surface indicates an uplift rate of 0.15 m/ka for Mary Ann Bay since the last interglacial maximum.

Clearly, a mechanism is required to explain the widespread, anomalously high level occurrences of last interglacial coastal strata and landforms in Tasmania. The mechanism must account for their pronounced seaward sloping nature (eg., Stumpys Bay Sands and the well developed beach ridge sequence on Robbins Island in NW Tasmania), and the absence of palaeosols or stepped topography characteristic of other emergent coasts (eg. Huon Peninsula, Papua New Guinea). The mechanism must also reconcile the apparent absence of uplifted Holocene coastal strata on mainland Tasmania (cf., King Island: Jennings, 1959; Murray-Wallace, unpublished data) and also the absence of high level last interglacial strata along the Victorian coastline (Murray-Wallace & Belperio, 1990)

As noted by Bowden & Colhoun (1984), the uplifted sequences cannot be attributed to glacio-isostatic or hydro-isostatic crustal readjustments. The former extent and thickness of ice in Tasmania during the Last Glaciation was not sufficient to account for the uplift recorded for the coastal sequences following deglaciation. Similarly, the continental shelf surrounding Tasmania is not sufficiently wide to permit hydro-isostatic uplift at the scale recorded by the last interglacial coastal facies.

Bowden & Colhoun (1984) attributed the high level occurrences of interglacial coastal strata and landforms to regional uplift in response to either hotspot activity or crustal underplating during the northward movement of the Australian Plate. Evidence consistent with the hotspot hypothesis includes: (1) crustal doming reflected in the geometry of the Stumpys Bay Sands and beach ridge plain on Robbins Island, (2) higher geothermal gradients on the NW coast of Tasmania (mound springs), (3) discharge of mantle CO_2 in deep mine waters and apparent ascent of basalt to the Bass Strait floor (Sutherland et al., 1989), (4) episodic, moderate to high seismicity of the region

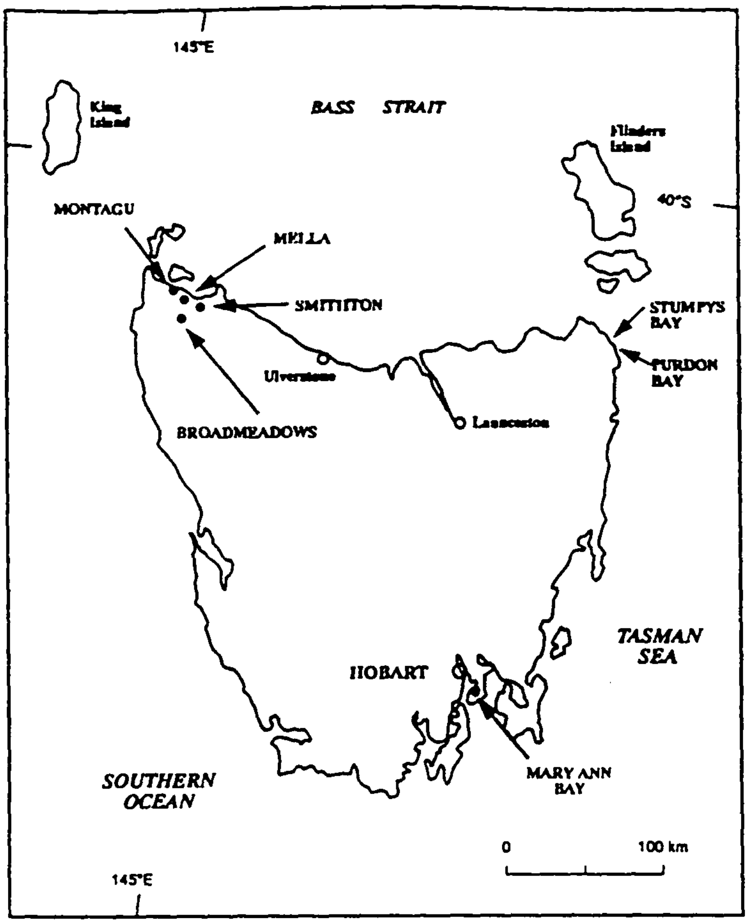

Figure 1. Location map of Mary Ann Bay and last interglacial sites on the NW coast of Tasmania.

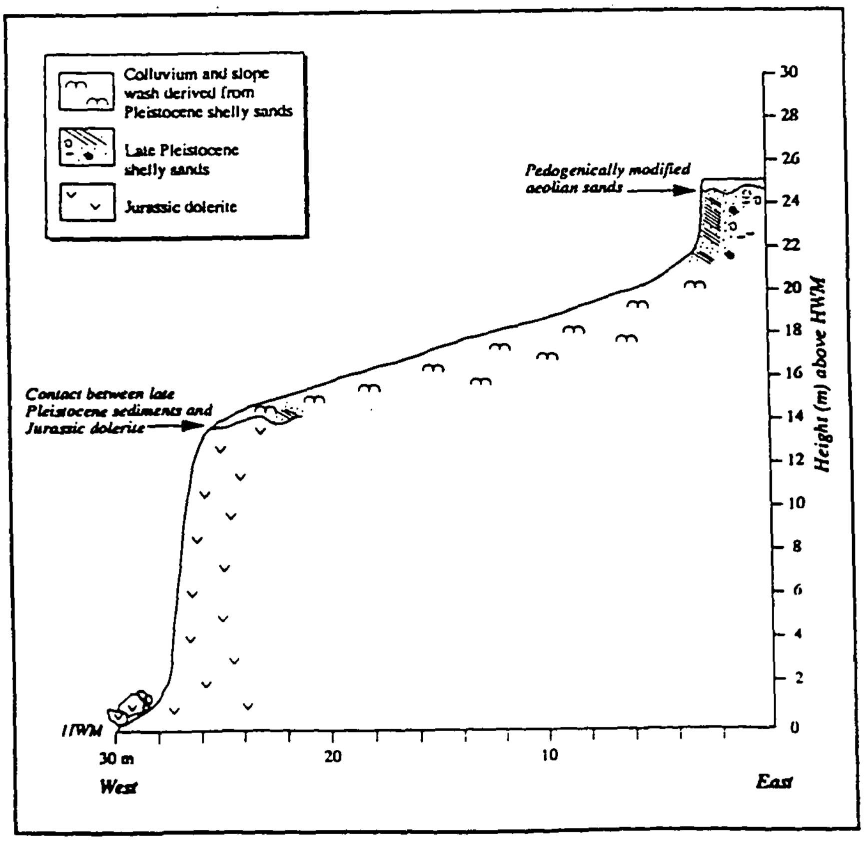

Figure 2. Cross-section illustrating the field setting of the late Pleistocene shell-rich sands at Mary Ann Bay. Scarp retreat has reworked part of this sequence on the debris slope immediately below the free face of the scarp.

Photo 1. View looking SSE towards the last interglacial shell bed sequence at Mary Ann Bay. Arrow indicates main outcrop location.

Photo 3. Disarticulated *Pecten meridionalis* and fragments of *Fulvia tenuicostata* in well bedded shell-rich sands, Mary Ann Bay.

Photo 2. Tabular cross-stratified shelly sands, Mary Ann Bay.
Camera lens cap = 52mm

Table 1 Summary of Quaternary dating methods applied to molluscan fossils from the shelly sands at Mary Ann Bay, Hobart, and comparison with 2 representative Holocene site.

LOCALITY	SPECIES	RADIOCARBON AGE BP*	AMINO ACID D/L RATIO (**) ('total acid hydrolysate') VAL	LEU	PRO	ASP	PHE	GLU	ESR DATA ED Value (gray)	95% conf. limit
Mary Ann Bay	*Pecten meridionalis*	39,900 +820/-740 (SUA - 2925)	0.24 ± 0.01	0.27 ± 0.002	-	0.44 ± 0.004	0.49 ± 0.01	-	104	94-116
Mary Ann Bay	*Fulvia tenuicostata*	-	0.22 ± 0.24	0.39 ± 0.02	0.38	0.36 ± 0.02	-	0.26 ± 0.02	133	99-149
The Spit, Ralphs Bay	*Fulvia tenuicostata*	6,510±80* (SUA-2294R)	0.11 ± 0.01	0.16 ± 0.03	0.11 ± 0.01	0.19 ± 0.01	012 ± 0.02	0.11 ± 0.01	19	16-22

Amino Acids : VAL - valine; LEU - leucine; PRO - proline; ASP - aspartic acid; PHE - phenylalanine; GLU - glutamic acid

* Calibrated radiocarbon age (cal BP) includes a correction for the marine reservoir effect for southern Australian coastal waters. This involved the subtraction of 480 ± 30 years from the conventional radiocarbon age (Libby half-life of 5568 years) according to the principles outlined by Gillespie and Polach (1979). Radiocarbon calibration tables used in these calculations are those of Klein *et al.*, (1982).

** The extent of amino acid racemisation becomes greater with increasing fossil age. Modern samples are characterised by D/L ratios close to zero, with older materials having D/L ratios that approach unity. The extent of racemisation for the Mary Ann Bay samples indicate ages of approximately 120,000 years BP.

(Denham, 1985; Michael-Leiba, 1989; Michael-Leiba and Gaull, 1989) and (5) the predicted position of the hotspot based on the northward migration of the Australian Plate (Wellman & McDougall, 1974; Sutherland, 1983; Sutherland et al., 1989).

In conflict with the hotspot hypothesis, is the suggestion that the geothermal gradients in Tasmania are likely to be sufficiently high to account for crustal doming, within the late Quarternary time framework that is constrained by geomorphologic and stratigraphic evidence (B.Thom pers. comm., 1990).

Understanding the cause of uplift requires a knowledge of the rates and relative timing of these processes. For example, was uplift a gradual and ongoing process, a geologically instantaneous (cataclysmic) event or a series of punctuated events? Relatively rapid uplift during the last interglaciation is supported by the pronounced seaward sloping character of the Stumpys Bay Sands and beach ridge complex on Robbins Island, the absence of palaeosols or a stepped topography in these sequences and the absence of uplifted Holocene sequences on mainland Tasmania. Counter to this argument, however, Holocene sequences would not be expected to be displaced vertically by more than approximately 1.6 m. This is based on the moderate uplift rates of 0.06 m/ka and 0.15 m/ka for the northwest coast of Tasmania and Mary Ann Bay respectively, and geophysical models that predict the lithospheric response to shifts in water loading (Nakada & Lambeck, 1989). The latter component is unlikely to exceed 0.6 m based on ice-mantle geophysical models (Nakada & Lambeck, 1989). The presence of 'interglacial' (eg. penultimate interglacial) coastal strata at elevations that exceed the last interglacial in Tasmania, also points to a history of uplift (Bowden & Colhoun, 1984). The validity of the ages ascribed to these 'older' coastal sequences, however, remains questionable.

Conclusions

Amino acid racemisation, electron spin resonance and indirect evidence from radiocarbon dating, point to a last interglacial age (oxygen isotope substage 5e) for the marginal marine strata at Mary Ann Bay in Tasmania. The sequence represents a critical reference site for understanding late Quaternary neotectonic processes in Tasmania, the scientific status of which clearly merits 'geological monument status'.

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Aminostratigraphy and electron spin resonance studies of late Quaternary sea level change and coastal neotectonics in Tasmania, Australia

by

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with 6 figures, 3 photos and 3 tables

Zusammenfassung. Zeugnisse für eine spätquartäre Meeresspiegeländerung und neotektonische Bewegungen der Küste sind entlang Tasmaniens Küste ausgedehnt vorhanden. Aufsteigende Küstenformen und Ablagerungen umfassen schmale marine Absätze, angehobene Flußterrassen und Brandungshöhlen, verlassene Kliffe und Tiden- und Subtiden-Sedimente in höherer Lage. Fossilienreiche Küstensedimente treten typisch zwischen 11m und 32 m über HWM (Hochwassermarke) auf, und mehrere Beispiele repräsentieren die höchsten Vorkommen der letztinterglazialen Küstensedimente Australiens. Aminosäure-Racemisierung und ESR bestätigen, daß viele dieser Sequenzen gleich alt sind. Diese Methoden und der indirekte Nachweis von Radiokarbon-Daten weisen auf ein letztinterglaziales Alter (oxygen isotope substage 5e) für diese aufgetauchten Erscheinungen hin. Die hohe Lage dieser Straten mit Rücksicht auf die global etablierten Niveaus für den letztinterglazialen Meeresspiegel wird einer neotektonischen Hebung zugeschrieben. Allerdings bleibt der Hebungsmechanismus problematisch. Eine Möglichkeit wären hotspot-Prozesse im Mantel. Es gibt keinen klaren Nachweis, um eine Abfolge des Aufsteigens während des Neogens nachzuweisen. Daher wird vorgeschlagen, daß die tektonische Hebung während des mittleren und späten Pleistozäns erfolgte. Zeugnisse holozäner Sequenzen sind auf der Hauptinsel Tasmania unzureichend, um festzulegen, ob diese tektonischen Prozesse weiterhin ablaufen.

Summary. Evidence for late Quaternary sea level change and coastal neotectonics occurs extensively around the Tasmanian coastline. Emergent coastal landforms and strata include narrow marine benches, elevated river terraces and sea caves, abandoned sea cliffs and intertidal and subtidal sediments at high elevations. Richly fossiliferous coastal sediments typically occur between 11–32 m above High Water Mark (HWM), and several examples represent the highest occurrences of last interglacial coastal strata on the Australian continent. Amino acid racemisation and electron spin resonance confirm that many of these sequences are coeval. These methods and indirect evidence from radiocarbon dating point to a last interglacial age (oxygen isotope substage 5e) for these emergent coastal features. The high elevation of these strata with respect to globally established levels for the last interglacial sea surface is attributed to neotectonic uplift. Although the uplift mechanism remains problematic, one possibility involves mantle hotspot processes. There is no clear evidence to support a history of emergence during the Neogene, thus tectonic uplift during the middle and late Pleistocene is suggested. Evidence from Holocene sequences on mainland Tasmania is insufficient to resolve whether these tectonic processes are still occurring.

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Résumé. Des preuves de changements de niveau de la mer et de néotectonique côtière pendant le Quaternaire récent se présentent tout le long de la côte de Tasmanie. Les formes côtières et les couches émergées comprennent: des replats marins étroits, des terrasses de rivières élevées, des grottes marines, des falaises marines abandonnées et des sédiments intertidaux et subtidaux à des altitudes élevées. Des sédiments côtiers riches en fossiles se présentent entre 11 et 32 m au-dessus du Niveau des Hautes Eaux (HWM), et plusieurs exemples représentent les occurrences les plus élevées des couches côtières du dernier interglaciaire sur le continent australien. La racémisation des acides aminés et la ESR confirment que beaucoup de ces séquences sont de meme âge. Ces méthodes ainsi qu'une contribution indirecte basée sur la datation ^{14}C indiquent un âge du dernier interglaciaire (Courbe ^{18}O: sous-étage 5e) pour ces traits côtiers émergés. La haute élévation de ces couches par rapport aux niveaux d'ensemble bien établis pour la surface de la mer au cours du dernier interglaciaire est attribué à un soulèvement néotectonique. Bien que le mécanisme du soulèvement demeure problématique, une possibilité implique des processus de hotspot dans le manteau. Il n'y a pas d'argument clair en faveur du soulèvement pendant le Néogène, de telle sorte que le soulèvement est attribué auf Pléistocène moyen et supérieur. Les faits d'observation provenant de séquences holocènes sur l'île principale de Tasmanie sont insuffisants pour répondre à la question de savoir si les processus tectoniques sont encore actifs.

1 *Introduction*

Evidence for Quaternary sea level change is provided by a range of coastal landforms and sediments in Tasmania. Their elevated positions in the landscape, relative ages and neotectonic significance, although anticipated by some (VAN DE GEER et al. 1979, BOWDEN & COLHOUN 1984) have remained problematic in detail. Early investigators did not appreciate that these features had been uplifted because Quaternary glacio-eustatic sea level curves of global applicability had not been elucidated (GILL & BANKS 1956; JENNINGS 1959, 1961; DAVIES 1959, 1961; CHICK 1971).

Middle Pleistocene to Holocene glacio-eustatic sea level curves of presumed global applicability (BLOOM et al. 1974, CHAPPELL 1974, 1983; CHAPPELL & SHACKLETON 1986) provide a framework to assess the ages of the Tasmanian coastal strata, and point to an 'interglacial' age for many of the Pleistocene sequences. Previous studies (VAN DE GEER et al. 1979, VAN DE GEER 1981, BOWDEN & COLHOUN 1984) ascribed a last interglacial age (oxygen isotope substage 5e) to them, but without directly dating the deposits. The anomalously high elevation of these coastal sequences compared with similar sediments of probable equivalent age on the Australian mainland suggests they are tectonically uplifted.

This paper examines the application of amino acid racemisation (AAR) and electron spin resonance (ESR) to dating coastal sediments in Tasmania. The principal study areas selected are the Hobart region and the northwest coast near Smithton (fig. 1), where richly fossiliferous Pleistocene coastal sediments provide the least ambiguous evidence for neotectonic uplift processes in Tasmania (cf. Stumpys Bay site of BOWDEN & COLHOUN 1984) and may potentially be dated more reliably than geomorphologic features resulting from erosional processes. The specific aims of the project were (1) to assess independently the ages of coastal strata previously ascribed last interglacial ages, (2) to evaluate critically evidence for neotectonic uplift of these sequences and (3) to consider possible processes responsible for these emergent features.

Amino acid racemisation and electron spin resonance dating have been extensively applied to Quaternary studies in the northern hemisphere (see WEHMILLER

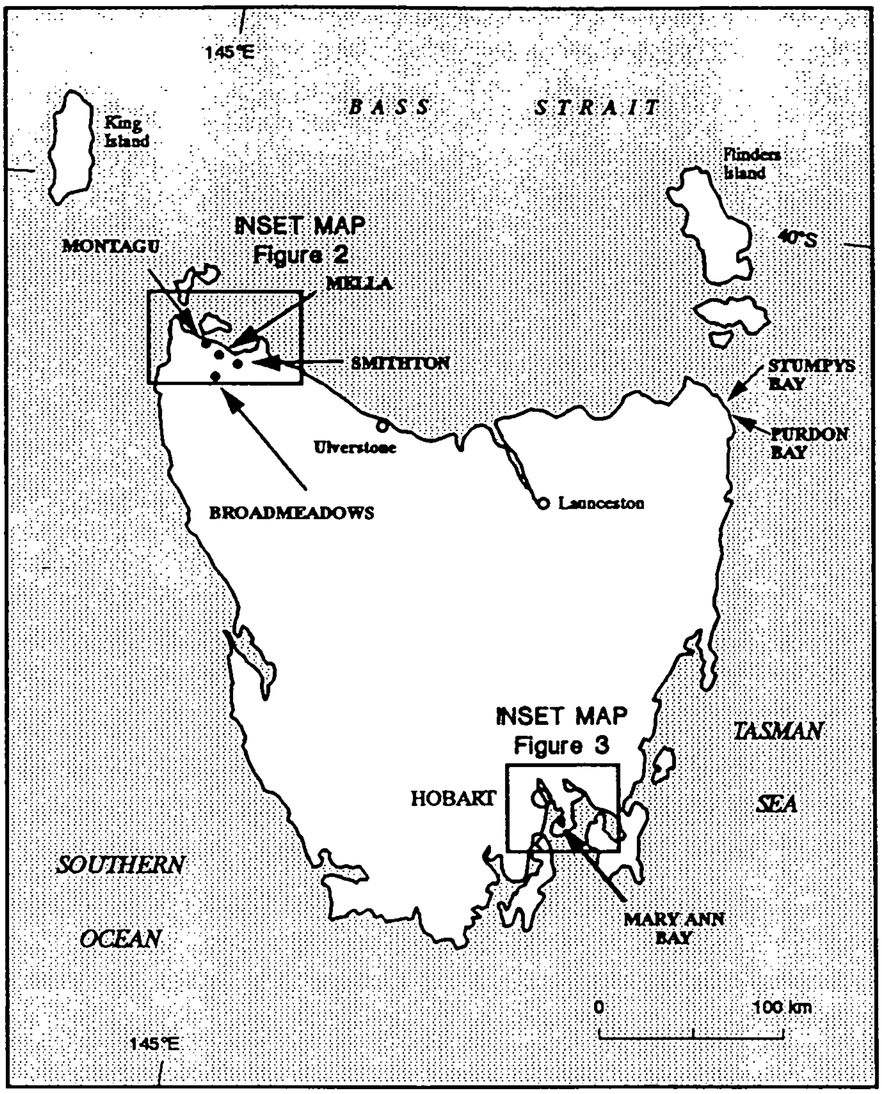

Fig. 1. Location map of sample sites in Tasmania. ●- last interglacial, O- Holocene.

1982, 1984a; MILLER & MANGERUD 1985 and GRUN 1989 for reviews). In contrast, these methods have been applied in Australian research only in recent years (see GOEDE 1988, 1989 and MURRAY-WALLACE & KIMBER 1987, 1988, 1989, 1990 for summaries). The relevance of these methods for dating the Tasmanian deposits centres on their applicability to a wide range of fossiliferous materials, the potentially wide time span they cover, and their small sample requirement.

Tasmania experiences a temperate maritime climate with cold wet winters. The island's rainfall distribution is variable. The annual rainfall exceeds some 1200 to 1400 mm on the west coast and attains levels of 3600 mm on the West Coast Range (COLHOUN et al. 1988). A rainshadow effect over the Midlands reduces average annual rainfall to less than 600 mm. Mean annual temperatures for Smithton and

Hobart are both 12.5 °C (Australian Climatic Averages 1981). The tidal range is 0.9 m at Hobart in the southeast but rises to 3 m at Smithton in the north-west of the island.

2 *Dating methods*

Amino acid racemisation

Analytical procedures and sampling strategies followed that of KIMBER & GRIFFIN (1987) and MURRAY-WALLACE & KIMBER (1987). Analyses of the N-pentafluoropropionyl D,L-amino acid isopropyl esters were undertaken using a 25 m fused silica Chirasil-L-Val capillary column and Hewlett Packard model 5890A gas chromatograph with a flame ionization detector. Analyses are for the 'total acid hydrolysate', a complex peptide mixture of varying molecular weights and free amino acids. Results are reported for several enantiomeric amino acids and include valine (VAL), leucine (LEU), proline (PRO), aspartic acid (ASP), phenylalanine (PHE) and glutamic acid (GLU). Results are not reported for isoleucine because of the poor baseline resolution during chromatography.

Analyses were undertaken on fossil bivalves including, *Fulvia tenuicostata, Glycymeris (Tucetilla) striatularis, Pecten meridionalis, Katelysia scalarina* and *Phacosoma coerulea*. Where possible molluscan species common to all sample sites were selected for AAR and ESR analyses to reduce the possibility of generic effects. Mollusc taxa characterised by moderate racemisation rates (MILLER & BRIGHAM-GRETTE 1989) were selected in this study. Stout shells were preferred as this permitted a more rigorous acid etch pretreatment to remove surface contamination (eg., non-indigenous amino acids). Approximately 10–20% by weight, for each shell was analysed by AAR, to reduce variability which may potentially arise when small fragments (<0.2 g) are analysed from large individuals (>30 g) (WEHMILLER 1984a). Multiple analyses were undertaken for each genus from a single deposit to assess intershell amino acid D/L ratio variation. The integrity of the analytical procedures was evaluated by analysing international interlaboratory comparison samples of WEHMILLER (1984b). Results were within two standard deviations of the grand mean of the international comparison.

Electron spin resonance

Summaries of the ESR technique and its application to a wide range of materials are provided by IKEYA (1988) and GRUN (1989), while GOEDE (1988) discusses some recent developments in age assessments of marine shell. Analytical methods used in this study follow GOEDE & HITCHMAN (1987). Analyses were performed on a JOEL JES-FE 3X ESR spectrometer at ambient temperatures at 100 kHz using a 4×10^{-5} T field modulation, an amplitude of 1000 and a microwave power of 5 mW.

Samples were prepared by crushing approximately 10 grams of cleaned shell, etched in 10% acetic acid, in a swing mill and separating the 125–250 μm size fraction by sieving. Etching with 10% acetic acid was again used to remove surface defects due to crushing. Etched samples were subdivided into five sub-samples, each weighing approximately 150 mg. Four subsamples were exposed to increments of gamma radiation using a ^{60}Co source while the fifth was left unirradiated.

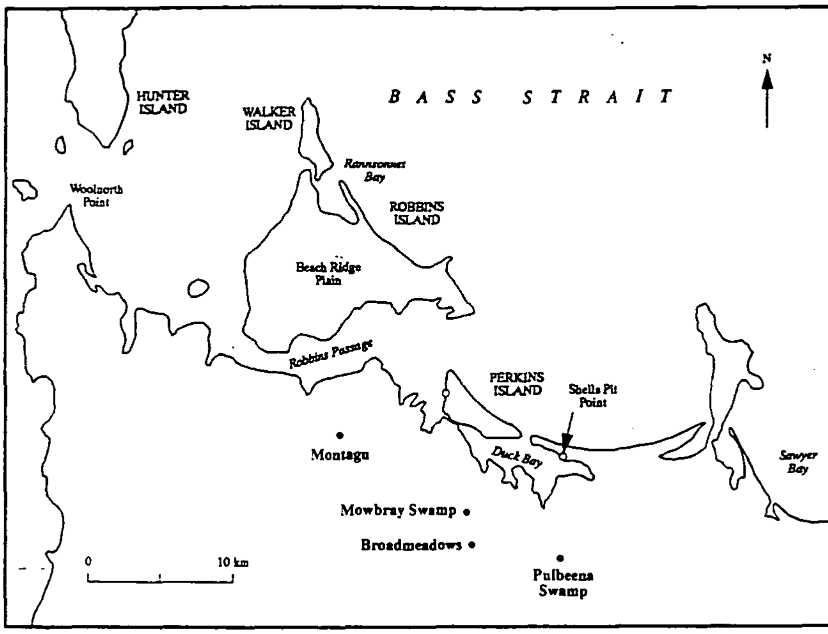

Fig. 2. Sample localities along the northwest coastline of Tasmania.

Peak intensities were determined five times for each sub-sample and the mean calculated. Peak intensities of sub-samples were plotted against corresponding ARD's and a linear regression line fitted to the points. The scaled value of the distance between the origin of the graph and the intersection point on the horizontal axis determines the gamma equivalent dose (ED value) of the sample. ED values (95% confidence level) were determined according to FRANKLIN (1986).

Aragonitic shell is normally used as ESR spectra of calcitic shells are strongly affected by the presence of Mn^{2+} lines that interfere with the spectral peak g = 2.0008 normally used for the determination of ED values. A technique to overcome this problem was suggested by NINAGAWA et al. (1985), who successfully applied it to a specimen of *Pecten albicans*. NINAGAWA's technique was successfully used on a specimen of *Pecten meridionalis* from Mary Ann Bay. ESR analyses were undertaken on species of the genera *Katelysia, Placamen, Glycymeris* and *Fulvia*.

Radiocarbon dating

Amino acid racemisation and electron spin resonance data were calibrated using radiocarbon dating according to the methods outlined by GUPTA & POLACH (1985). Radiocarbon ages (BP) for molluscs were corrected for the marine 'reservoir effect' (GILLESPIE & POLACH 1979) and converted to sidereal (calendar) years using calibration tables of KLEIN et al. (1982). The hydrochloric acid (8M) residue from the carbon dioxide evolution procedure of radiocarbon dating was analysed using amino acid racemisation techniques outlined by MURRAY-WALLACE & BOURMAN (1990). This provided direct comparison of the extent of amino acid racemisation with radiocarbon ages and applies for radiocarbon samples SUA-2833, SUA-2834 and SUA-2925 (tables 1 and 2).

Table 1 Summary of radiocarbon age assessments of Holocene and late Pleistocene mollusca from Tasmania.

Locality	Species	Lab code	Conventional age (BP)	Calibrated age (cal BP)*
Shelly Beach, Ralphs Bay	*Katelysia scalarina*	SUA-2293	3140 ± 50	2770 ± 110
The Spit, Ralphs Bay	*Katelysia scalarina*	SUA-2294 R	6150 ± 60	6510 ± 80
Shell Pits Point	*Glycymeris (Tucetilla) striatularis*	SUA-2833	5700 ± 70	6020 ± 140
Shell Pits Point	*Fulvia tenuicostata*	SUA-2928	6630 ± 80	7060 ± 100
Five Mile Beach	*Phacosoma coerulea*	SUA-2834	37,500 ± 600	–
Mary Ann Bay	*Pecten meridionalis*	SUA-2925	39,900 + 800 – 700	–

* Calibrated radiocarbon ages (cal BP) include a correction for the marine reservoir effect for southern Australian coastal waters. This involved the subtraction of 480 ± 30 years from the conventional radiocarbon age (Libby half-life of 5568 years) according to the principles outlined by GILLESPIE & POLACH (1979). Radiocarbon calibration tables used in these calculations are those of KLEIN et al. (1982).

3 *Geomorphological and lithostratigraphic framework*

Previous investigations

Direct and indirect evidence for Quaternary sea level change is extensively represented around the Tasmanian coastline. Along the northwest coast, near Smithton, numerous well developed peat beds occur extensively within topographic depressions between dune ridges. They are in turn buried by a thin sheet of cover sands with moderately developed soil horizons. Well documented examples occur at Pulbeena (COLHOUN et al. 1982b) and at various sites within the Mowbray Swamp lowland (GILL & BANKS 1956) (fig. 2). The importance of these sequences in providing an upper limit (minimum age) for the underlying interglacial coastal facies was noted by COLHOUN et al. (1982b). They undertook radiocarbon dating and extensive palynologic analyses of a 5 m thick peat sequence at Pulbeena Swamp (fig. 2) and obtained radiocarbon ages for the peats that ranged between 22,130 ± 180 BP (GrN-7689) to 53,400 $^{+3700}_{-2500}$ BP (GrN-9459).

The similar lithologic characteristics and geomorphologic context of the cover sequence at Montagu, Mowbray Swamp and Broadmeadows (fig. 2), to the Pulbeena Swamp sequence indirectly points to the last interglacial age (oxygen isotope substage 5e) of the underlying coastal facies for each of these sites. GILL & BANKS (1956) reported two dates from Mella (herein the Mowbray Swamp site), on marl and peat respectively, that yielded ages of > 37,760 yrs (Yale University Geochronometric Laboratory), suggesting that the age of these sediments exceeds the practical limits of radiocarbon dating. This is consistent with the lithostratigraphic correlation of these

Table 2 Extent of amino acid racemisation in late Quaternary molluscan fossils from Tasmania.

Site locality	Species	Amino acid D/L ratio ("total acid hydrolysate") VAL	LEU	PRO	ASP	PHE	GLU	No of analyses	Geologically expected age
Montagu	*Fulvia tenuicostata*	0.15 ±0.002	0.35 ±0.05	0.43 ±0.09	0.37 ±0.04	0.47 ±0.05	0.19 ±0.03	4	Late Pleistocene
Montagu	*Glycymeris (Tucetilla) striatularis*	0.15 ±0.007	0.30 ±0.01	0.42 ±0.03	0.47 ±0.06	0.39 ±0.03	0.20 ±0.004	3	Late Pleistocene
Broadmeadows	*Glycymeris (Tucetilla) striatularis*	0.18 ±0.02	0.31 ±0.04	0.49 ±0.03	0.49 ±0.06	0.43 ±0.05	0.25 ±0.01	6	Late Pleistocene
Mowbray Swamp	*Glycymeris (Tucetilla) striatularis*	0.20 ±0.02	0.47 ±0.03	–	0.53 ±0.03	0.47 ±0.06	0.27 ±0.02	4	Late Pleistocene
Mary Ann Bay	*Fulvia tenuicostata*	0.22 ±0.04	0.39 ±0.02	0.38	0.36 ±0.02	–	0.26 ±0.02	4	Late Pleistocene
Mary Ann Bay	*Pecten meridionalis*	0.24 ±0.01	0.27 ±0.002	–	0.44 ±0.004	0.49 ±0.01	–	1*	Late Pleistocene
"The Spit" Ralphs Bay	*Katelysia scalarina*	0.05 ±0.002	0.14 ±0.02	0.18 ±0.01	0.28 ±0.001	0.11 ±0.001	0.09 ±0.006	1	Holocene
"The Spit" Ralphs Bay	*Fulvia tenuicostata*	0.11 ±0.01	0.16 ±0.03	0.11 ±0.01	0.19 ±0.01	0.12 ±0.02	0.11 ±0.01	1	Holocene
Shell Pits Point N W Tasmania	*Glycymeris (Tucetilla) striatularis*	0.09 ±0.01	0.17 ±0.01	–	0.33 ±0.01(?)	0.16 ±0.05	0.15 ±0.01	1*	Holocene
Five Mile Beach S E Tasmania	*Phacosoma coerulea*	0.22 ±0.01	–	0.52	0.28	0.40 ±0.02	0.25 ±0.02	1*	Holocene

Amino Acids VAL – valine; LEU – leucine; PRO – proline; ASP – aspartic acid; PHE – phenylalanine; GLU – glutamic acid
* residue from acid evolution of CO_2 for radiocarbon sample preparation. Several shells used.

deposits. A subsequent study of the stratigraphy and pollen content by VAN DE GEER et al. (1986) provided a radiocarbon date of > 52,000 BP (GrN-9743) at a 125 cm depth in a 200 cm thick peat layer at Mowbray Swamp and a basal radiocarbon date of 27,600 BP (GaK-6324) at a depth of 100 cm at Broadmeadows Swamp.

Geomorphologic evidence for fossil shorelines near Ulverstone, along the central north coast of Tasmania, was examined by CHICK (1971), who recognised former high sea level stands at 34, 20, 14, 11 and 1 m above present HWM. He suggested the 1 m level to be a Holocene shoreline, and the others to date from the last interglacial.

A sequence of beach ridges occurs at Stumpys Bay, on the northeast coast of Tasmania (BOWDEN 1981). They attain an inland level of 32.5 m above HWM, a maximum thickness of 8 m and overlie granite. The 2 km wide strandplain and six associated ridges slopes seaward with a gradient of approximately 12.5 m/km (BOWDEN & COLHOUN 1984). Weathered sponge spicules attest to a marine origin for the sediments and no evidence was found of reworking of the sponge spicules from older materials. They concluded the beach ridge sand sheet complex was deposited during a single marine transgression (last interglacial: oxygen isotope substage 5e), based on the absence of depositional breaks, palaeosols or a stepped topography (cf., Huon Peninsula, Papua New Guinea).

Other elevated marginal marine features attributed to the last interglacial in Tasmania include marked marine levels between 18 to 21 m and 30 to 37 m on Flinders Island (KERSHAW & SUTHERLAND 1972) and a prominent level at 20 m on King Island (JENNINGS 1959, 1961). Other former high marine levels have been noted in southeastern Tasmania by DAVIES (1959) and possibly at Rockbank in northeastern Tasmania (BOWDEN & COLHOUN 1984). Their age remains unclear. None of the previous studies, however, has confirmed the age of the emerged coastal strata. This study represents the first systematic attempt to date the biota from these deposits.

4 *Pleistocene coastal sediments: lithostratigraphy*

Late Pleistocene sequences

Richly fossiliferous, unconsolidated quartz sands occur extensively within a prominent topographic depression west of Smithton (figs. 1 and 2). The lowland referred to as Mowbray Swamp by GILL & BANKS (1956), is in part underlain by Cambrian dolomite and extends some 19 km inland with an average width of approximately 9 km. Higher relief surrounding Mowbray Swamp, attains levels of 60 m above sea level.

Shells were collected from Broadmeadows and Mowbray Swamps, two sites within the Mowbray Swamp lowland of GILL & BANKS (1956). Shells were also collected from a site at Montagu, some 18 km WNW from Smithton, located on an adjacent area of low relief, the Montagu Plains (figs. 1 and 2).

Several characteristics are common to these three deposits. The molluscan fauna are very well preserved, with original pigmentation and nacreous lustre on many individuals. The high calcium carbonate content of the groundwaters, derived from subsurface solution of Cambrian dolomites is responsible for their excellent preservation. The shells are well buried at depths generally exceeding 1 m and the elevation

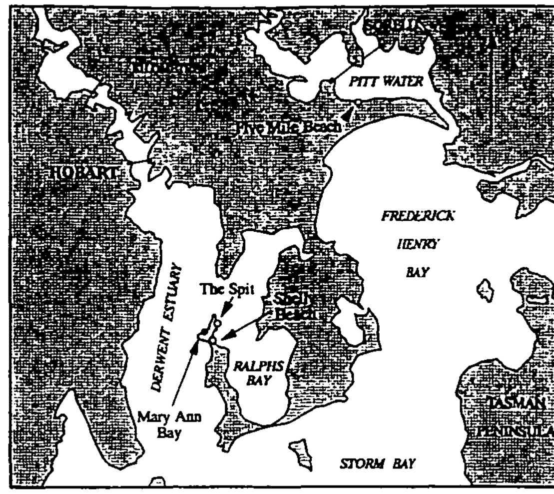

Fig. 3. Sample localities in the Hobart region.

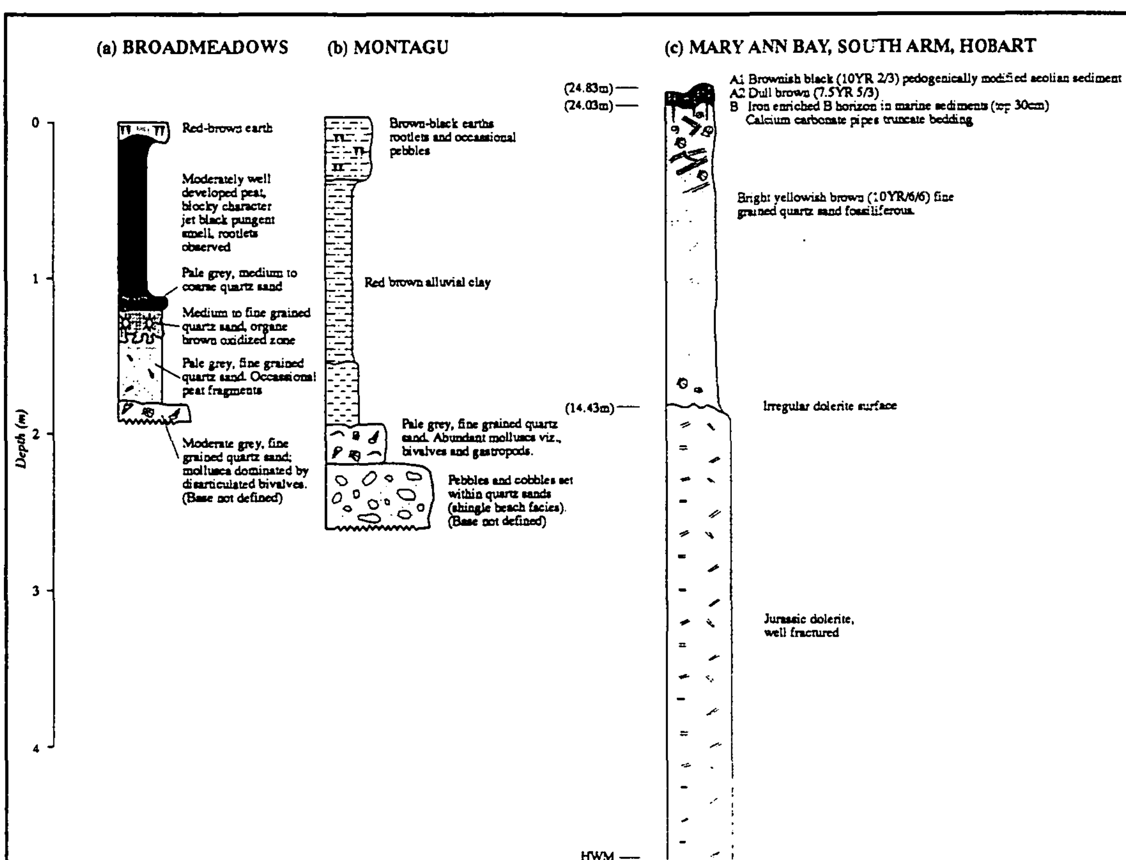

Fig. 4. Stratigraphic sections of late Pleistocene coastal sediments. (a) Broadmeadows and (b) Montagu, northwest coast of Tasmania and (c) Mary Ann Bay, South Arm, Hobart.

of the three deposits with respect to present HWM all exceed 10 m. The three sites are located between 3.5 and 6 km from the sea.

Broadmeadows

Broadmeadows is situated some 6 km inland from the present coastline (fig. 2). Molluscs were obtained from a pit adjacent to the Bass Highway. The top of the pit was 1 m below the level of the surrounding plain, and some 13 m above HWM. Shells were obtained from a basal shell bed comprising, moderate grey, fine grained quartz sand and abundant, predominantly disarticulated bivalves. The thickness of this unit is undetermined although the upper most 10 cm were penetrated (fig. 4a). The top of the shell bed is 1.7 m below the ground surface.

A pale grey, fine grained quartz sand with occasional, widely scattered peat fragments overlies the marine unit with a sharp contact. This unit is 40 cm thick and its upper surface is irregular, grading into a 20 cm thick oxidized zone of orange-brown coloured, medium to fine grained quartz sand. A 10 cm thick pale grey, medium to coarse grained quartz sand overlies the oxidized zone, which in turn is overlain by a moderately well developed jet black, pungent smelling, blocky peat (90 cm), with numerous well preserved rootlets. A redbrown earth (10 cm) mantles the peat. COLHOUN et al. (1982a) document 51 molluscan species from this site.

Montagu

Shells were excavated from a marine unit slightly in excess of 2 m below the ground surface and located some 3.5 km from the present coastline, at an elevation of 11 m above HWM (fig. 2). A small pit revealed a 25 cm thick marine unit (fig. 4b), comprising pale grey fine grained quartz sand with an abundant molluscan fauna of disarticulated fossil bivalves and gastropods. COLHOUN et al. (1982a) document sixty-eight molluscan species from this site. The shell bed rests on a shingle beach facies consisting of numerous bladed siltstone cobbles and pebbles set in quartz sand. A 2 m thick sequence of red-brown alluvial clays and black-brown earths, mantles the marine facies.

Mowbray Swamp

Mollusca collected for dating were obtained from a water bore under construction near Mella, in Mowbray Swamp (figs. 1 and 2). The shells occurred at a depth of between 6 and 9 m. Precise details of the lithostratigraphy could not be ascertained because of the drilling method used. A 4.5 m thick peat was underlain by a quartz sand. The shells were confined to the lower section of the quartz sand unit, as noted at Broadmeadows and Montagu.

Mary Ann Bay

Moderately to finely comminuted molluscan fossils occur in well bedded shallow water, middle shoreface sediments exposed within an actively eroding cliff at Mary Ann Bay near, Hobart (figs. 1, 3 and 4c and photos 1, 2 and 3). The sequence attains a maximum thickness of 9.6 m and unconformably overlies Jurassic dolerite. Several cosets of fining upward tabular cross-stratification occur within the sequence. The base of each coset is defined by coarse shell fragments and disarticulated *Pecten* spp., that grade into more finely comminuted shells and terminates in medium to fine grained quartz sands with a smaller component of comminuted shell (i.e., long axes 2–3 mm) (photos 2 and 3). The shell rich sediments are overlain by dull brown (7.5 YR 5/3) to brownish black (10 YR 2/3) pedogenically modified aeolian sands of variable thickness (0.5–1 m). The top of the subtidal coastal facies is an erosional contact and occurs some 24 m above present HWM. The cliff exposure is terraced with an irregular bench that trends seawards and defines the contact between the Jurassic dolerite and the overlying Quaternary sequence.

5 *Holocene sequences*

Fossil bivalves were collected from two Holocene sequences along the northwest coastline of Tasmania (fig. 2) and three Holocene sequences in the Hobart region (fig. 3) to calibrate AAR and ESR results for Pleistocene sequences. Results from Holocene sequences also assist the interpretation of racemisation kinetics and provide a framework to assess critically, evidence for late Pleistocene sea levels and neotectonics.

Five Mile Beach

Numerous specimens of mollusca for dating (tables 1,2,3) were obtained from a sequence of clean quartz sands (fig. 3). The shells which occur at a level of up to 1.5 m above HWM and were buried by a 1.2 m sequence of aeolian dune sand with immature podzol development are intercalated with a semi-indurated calcium carbonate horizon. A Holocene age is indicated by their geomorphologic setting.

The Spit, Ralphs Bay

A Holocene midden resting on coastal sediments containing an abundant molluscan fauna is exposed in a low cliff forming the outer edge of a cuspate foreland at Ralphs Bay near Hobart (fig. 3). Molluscs were collected from the marine unit, which is overlain by a 0.7 m thick midden and soil. Both disarticulated and articulated shells were represented within this deposit.

Shelly Beach

The sample was collected from a +0.3 m thick shelly beach deposit, exposed only after storm wave erosion at the base of a low cliff in Ralphs Bay, near Hobart (fig. 3). The sediments do not require a higher sea level for their deposition. They are overlain by 0.3 m of charcoal-rich aboriginal shell midden with *Ostrea angasi* and *Mytilus planulatus* as dominant species. This in turn is overlain by 0.3 m of aeolian sand with occasional shells. The beach deposit has been radiocarbon dated (table 1).

Photo 1. View looking NE towards the shell bed sequence at Mary Ann Bay, that is here considered last interglacial in age. Arrow indicates main outcrop location.

Shell Pits Point

Disarticulated mollusca were collected for dating (tables 1,2,3) from a Holocene beach ridge (fig. 2) mantled by an immature, grey soil also containing shells. The shells were excavated from a small, rapidly eroding cliff and were buried at a depth of 0.6 m in a tightly compacted mollusc-dominated grainstone. No matrix or cement was evident. The limestone rests unconformably on columnar jointed Tertiary basalt.

Perkins Island

Molluscs were collected from a fine grained clean quartz sand which occurs 1.5 m below a series of well developed aeolian dune ridges that display tabular and trough cross stratification (fig. 2).

6 *Results*

Radiocarbon dating

Radiocarbon dating of *Katelysia* spp., *Fulvia* spp., and *Glycymeris* spp., from Holocene coastal sequences yielded calibrated radiocarbon ages consistent with the geomorphologic and stratigraphic context of these sequences (table 1).

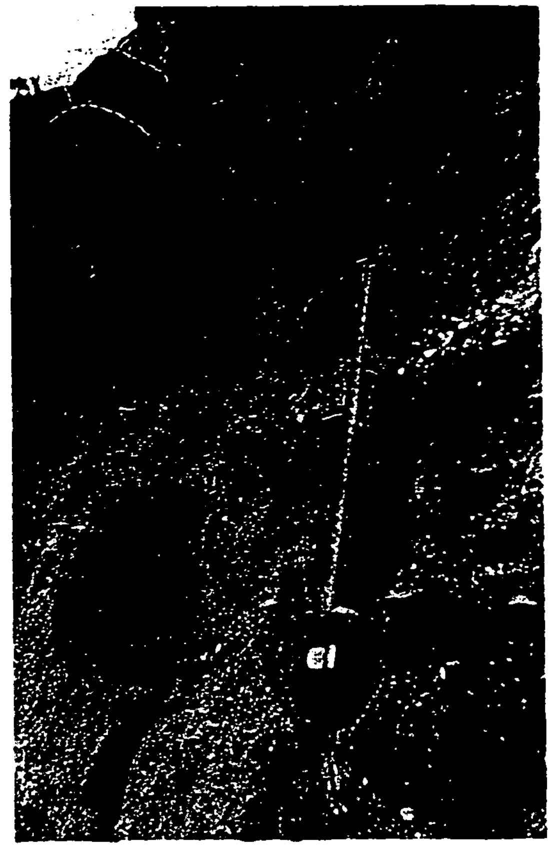

Photo 2. Tabular cross-stratified shelly sands, Mary Ann Bay. Camera lens cap = 52 mm.

Photo 3. Disarticulated *Pecten meridionalis* and *Fulvia tenuicostata* in well bedded shell-rich sands, Mary Ann Bay.

In contrast, radiocarbon dating of three specimens of *Phacosoma coerulea* from the Five Mile Beach site, indirectly points to a last interglacial age for the individuals (table 1) because as GUPTA & POLACH (1985) noted, the effect of 1% contamination by 'modern' carbon on a fossil of last interglacial age is to yield an apparent radiocarbon age of approximately 37,000 years BP. Similarly, the extent of racemisation for a range of amino acids in *Phacosoma coerulea* (from the acid residue of the radiocarbon sample, SUA-2834), indicates a last interglacial age by analogy with the other late Pleistocene fossils reported in table 2 and temperature dependent models of amino acid D/L ratio variation with latitude (MURRAY-WALLACE et al. 1991). ESR analyses on different samples suggest that the deposit contains a mixed assemblage of reworked late Pleistocene fauna with a Holocene component. For example, the low ESR value for *Fulvia tenuicostata* (table 3), a very fragile shell unlikely to be reworked in one piece, suggests that the sediment is probably Holocene by analogy with radiocarbon calibrated ESR data from other Holocene sequences (cf. tables 1 and 3).

Table 3 Summary of ESR data from Pleistocene and Holocene marginal marine sequences in Tasmania.

Sample No	Species	ED (gray)	95% conf. limits
Montagu			
T8	*Fulvia tenuicostata*	102	91–116
T11	*Glycymeris (Tucetilla) striatularis*	66	60– 71
T21	*Placamen placida*	161	148–176
T30	*Glycymeris (Tucetilla) striatularis*	63	59– 68
F55	*Fulvia tenuicostata*	93	86–101
F57	*Fulvia tenuicostata*	84	77– 92
Mowbray Swamp			
T13	*Glycymeris (Tucetilla) striatularis*	72	67– 74
T18	*Paphies (Atactodea) erycinaea*	76	70– 81
T22	*Placamen placida*	166	150–184
Broadmeadows			
T14	*Glycymeris (Tucetilla) striatularis*	94	83–105
T27	*Placamen placida*	115	105–127
T29	*Tucetona flabellatus*	81	75– 87
Mary Ann Bay			
F54	*Fulvia tenuicostata*	133	99–149
F56	*Fulvia tenuicostata*	112	102–123
T6	*Pecten meridionalis*	104	94–116
Five Mile Beach			
T17	*Phacosoma coerulea*	98	89–109
T24	*Mactra rufescens*	46	40– 53
T9	*Fulvia tenuicostata*	24	19– 29
Shell Pits Point			
T10	*Fulvia tenuicostata*	26	21– 30
T16	*Katelysia rhytiphora*	18	14– 21
T23	*Placamen placida*	40	37– 42
Perkins Island			
T7	*Fulvia tenuicostata*	20	16– 24
T12	*Glycymeris (Tucetilla) striatularis*	15	10– 20
The Spit (Ralphs Bay)			
T15	*Katelysia scalarina*	13	10– 16
F74(1)	*Fulvia tenuicostata*	19	16– 22
F79(1)	*Katelysia scalarina*	13	12– 15
Shelly Beach (Ralphs Bay)			
F68(1)	*Fulvia tenuicostata*	6	5– 8
F68(2)	*Fulvia tenuicostata*	10	8– 13

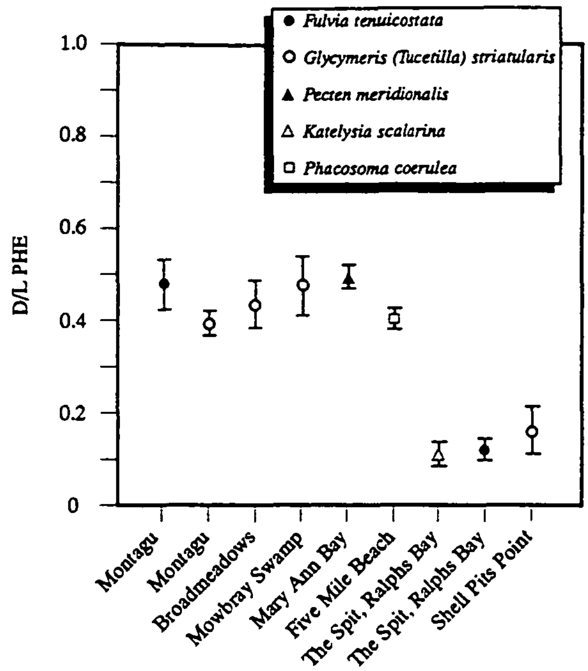

Fig. 5. Extent of racemisation for the amino acid phenylalanine (PHE), 'total acid hydrolysate' in late Pleistocene and Holocene molluscan fossils from coastal strata in Tasmania.

Radiocarbon dating was also undertaken on 5 whole, disarticulated valves of *Pecten meridionalis* from Mary Ann Bay. In view of the difficulties of applying uranium-series disequilibrium to the dating of fossil molluscs, radiocarbon dating was undertaken to validate indirectly, the results from amino acid racemisation and electron spin resonance. The radiocarbon age of $39{,}900^{+800}_{-700}$ BP (SUA-2925) indicates that minor contamination (ca. <1%) by Holocene carbonate, which could not be isolated during sample pretreatment, may have resulted in the apparent age reported (table 1).

Amino acid racemisation

The relative extent of racemisation for all amino acids, both for Pleistocene and Holocene fossils, is in accord with published results (Lajoie et al. 1980, Murray-Wallace et al. 1988a, b, c) (table 2). Amino acid data for the species studied, fulfill the suitability criteria for racemisation dating (Wehmiller 1984a). A partitioning in the extent of amino acid racemisation is evident for molluscs, independently ascribed Holocene and Pleistocene ages based on geomorphologic, stratigraphic and palaeontologic relationships and radiocarbon dating (fig. 5). The extent of racemisation for a range of amino acids is consistently greater in the Pleistocene fossils than their Holocene equivalents (table 2). The similarity in extent of racemisation for the mollusca from Montagu, Mowbray Swamp and Broadmeadows on the northwest coast and Mary Ann Bay in the Hobart region, suggests they represent a common age, given the assumption that the integrated effect of all other parameters influencing racemisation between sample sites were similar during their diagenetic history. The validity of this assumption can be assessed partly, in the context of previous investigations (SCHROEDER & BADA 1976, WILLIAMS & SMITH 1977, WEHMILLER 1982, 1984a), which indicate that the calcium carbonate matrix of shells represents an effective chemical buffer, and retains indigenous peptide residues for protracted periods. Furthermore, the pH ranges typically experienced in the environments sampled in this study have been demonstrated not to influence racemisation (BADA 1985).

Comparison of the extent of amino acid racemisation in the late Pleistocene molluscan fossils with samples of equivalent age, from the Australian mainland demonstrates a latitudinal effect on D/L ratio variation (MURRAY-WALLACE et al 1991). These data reflect the contrasting diagenetic temperature histories of the different sample sites and the data set for the Pleistocene taxa from Tasmania are in accord with this relationship (MURRAY-WALLACE et al. 1991). A numerical age assessment on the late Pleistocene mollusca from Tasmania reveals a mean age of 94,200 ± 28,300 BP based on the extent of valine racemisation. The error term allows for an uncertainty of 2 °C in the diagenetic temperature history. The numerical age was derived through a comparison of the Tasmanian Pleistocene data set with uranium-series calibrated amino acid data from South Australia and the integrated rate expression for amino acid racemisation (SCHWEBEL 1984, MURRAY-WALLACE et al. 1988a, 1991; WILLIAMS & SMITH 1977). In a global context, the Tasmanian Pleistocene amino acid data are in accord with northern hemisphere results for sites with similar contemporary mean annual temperatures (WEHMILLER 1982, 1984a) and highlight the potential of using amino acid data in late Quaternary global correlation programs.

Electron spin resonance

Examination of ESR results (table 3) reveals that at sites where shells of *Placamen placida* have been analysed, the ED values are significantly higher than those obtained for other species. Their removal from the distribution of ED values indicates that these values tend to group into two clusters. The first cluster with values ranging between 5 and 30 gray points to a Holocene age for the sequences at Ralphs Bay, Shelly Beach, Shell Pits Point and Perkins Island by analogy with radiocarbon dating (table 1). The second cluster with values between 60 and 120 gray is consistent with a last interglacial age (i.e., Mowbray Swamp, Broadmeadows, Montagu and Mary Ann Bay). Due to the siliceous matrix with its low uranium content this range is significantly lower than in last interglacial calcarenite environments where the typical range is between 100 and 200 gray (GOEDE 1989; GOEDE & HITCHMAN 1987; HEWGILL et al. 1983).

7 *Discussion*

Amino acid racemisation and electron spin resonance add further weight to the last interglacial age (oxygen isotope substage 5e) for numerous high level occurrences of coastal sediments in Tasmania, previously inferred this age. In a critical review of last

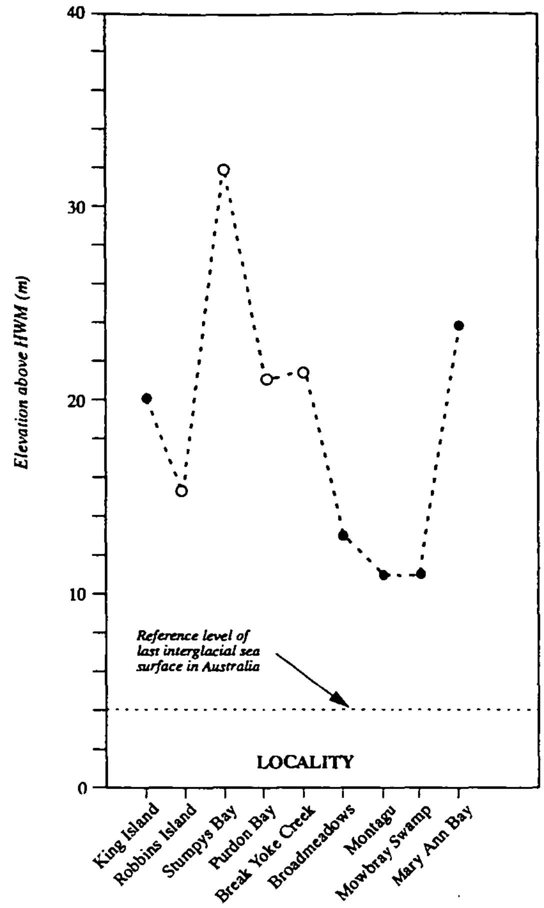

Fig. 6. Late Pleistocene (oxygen isotope substage 5e) shoreline elevations from Tasmania compared with the +4m (mean sea level) reference level for the last interglacial sea surface proposed by MURRAY-WALLACE & BELPERIO (1990). Solid circles indicate sequences that have been directly dated as last interglacial by amino acid racemisation and electron spin resonance in conjunction with geomorphologic and lithostratigraphic evidence, and includes unpublished amino acid data for King Island (MURRAY-WALLACE). Open circles refer to sites ascribed last interglacial ages based on inference and geomorphologic and lithostratigraphic evidence.

interglacial coastal sedimentation in Australia, MURRAY-WALLACE & BELPERIO (1990) were unable to substantiate the +6 m reference level for the last interglacial sea surface, for settings that had not been disrupted by demonstrable tectonism. They concluded from a study of a range of widely separated sites that sea levels during the last interglacial maximum generally did not exceed 4 m above Australian Height Datum (AHD-mean sea level).

In contrast, coastal sediments of this age in Tasmania, typically exceed 11 m above HWM (VAN DE GEER et al., 1979; COLHOUN et al. 1982a; BOWDEN & COLHOUN 1984) (fig. 6). At Mary Ann Bay they occur up to 24 m above HWM and represent the highest level occurrence of last interglacial coastal sediments on the Australian continent. Similar levels are documented by BOWDEN & COLHOUN (1984) for marine sands at Purdon Bay and Break Yoke Creek in northeastern Tasmania (fig. 1), but the last interglacial age ascribed to these sequences has yet to be confirmed.

Clearly, a mechanism is required to explain the widespread, anomalously high level occurrences of last interglacial coastal strata and landforms in Tasmania. BOWDEN & COLHOUN (1984) dismissed glacio-isostatic or hydroisostatic crustal readjustment as possible mechanisms and attributed the high level occurrences of interglacial coastal strata and landforms to regional uplift in response to either hotspot activity or crustal underplating during the northward movement of the Australian Plate. Evidence consistent with the hotspot hypothesis include: (1) crustal doming reflected in the geometry of the Stumpys Bay Sands and beach ridge plain on Robbins Island, (2) higher geothermal gradients on the NW coast of Tasmania (mound springs) (CULL 1982), (3) discharge of mantle CO_2 in deep mine waters and apparent ascent of basalt to the Bass Strait floor (SUTHERLAND et al. 1989), (4) moderate to high seismicity of the region (DENHAM 1985; MICHAEL-LEIBA 1989; MICHAEL-LEIBA & GAULL 1989) and (6) the predicted position of the hotspot based on the northward migration of the Australian Plate (SUTHERLAND 1983; SUTHERLAND et al. 1989).

Understanding the cause of uplift requires a knowledge of the rates and relative timing of these processes. Relatively rapid uplift during the last interglaciation is supported by the pronounced seaward sloping character of the Stumpys Bay Sands and beach ridge complex on Robbins Island (BOWDEN & COLHOUN 1984), the absence of palaeosols or a stepped topography in these sequences or uplifted Holocene sequences on mainland Tasmania. Counter to this argument, however, Holocene sequences would not be expected to be displaced vertically by more than approximately 1.6 m. This is based on the moderate uplift rates of 0.006 m/ka and 0.15 m/ka for the northwest coast of Tasmania and Mary Ann Bay respectively, and geophysical models that predict the lithospheric response to shifts in water loading (NAKADA & LAMBECK 1989). The latter component is unlikely to exceed 0.6 m based on ice-mantle geophysical models (NAKADA & LAMBECK 1989). The assumptions of a constant rate of uplift and a + 4 m level for the last interglacial sea surface (oxygen isotope substage 5e) are also implicit in this interpretation (MURRAY-WALLACE & BELPERIO 1990).

In contrast, the presence of 'interglacial' (eg., penultimate interglacial) coastal strata at elevations that exceed the last interglacial in Tasmania, points to a long history of uplift (BOWDEN & COLHOUN 1984). At present insufficient data are available to answer conclusively (1) when uplift occurred and (2) whether these processes are still occurring. More importantly, the question of whether present geological and geophysical models can adequately account for these uplifted sequences remains unclear. The resolution of these issues presents a major challenge to future studies of the Quaternary stratigraphic and neotectonic history of Tasmania.

8 *Conclusions*

(1) Concordant results from amino acid racemisation and electron spin resonance indicate that several high level occurrences of coastal strata along the NW and SE coasts of Tasmania are coeval. Amino acid and electron spin resonance data confirm that these sequences are older than Holocene and were probably deposited during

the last interglacial (125,000 years BP; substage 5e of the deep sea oxygen isotope record). These results are also constrained by the Huon Peninsula sea level curve and the deep sea oxygen isotope record of global ice volume.

(2) The anomalously high elevation of these strata with respect to the level estimated globally for the last interglacial sea surface is attributed to tectonic uplift. The processes responsible for these uplifted sequences are not understood, although a mantle hotspot mechanism should not be excluded.

(3) Relative stratigraphic relationships examined in this study and geomorphologic evidence hint at the likelihood of differential tectonic uplift, although evidence from Holocene sequences is insufficient to resolve the question as to whether these tectonic processes are still operative.

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Ms L. Turner of the Tasmanian Museum and Art Gallery kindly identified some mollusca. Ms G. Taylor (University of Sydney) for technical assistance with radiocarbon dating. Funds were provided by the University of Tasmania and the Australian Research Council (ARC 89/044). The manuscript was read at draft stage by Drs R. P. Bourman and A. P. Belperio.

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Trace element variations and dating of a Late Pleistocene Tasmanian speleothem

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ABSTRACT

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A calcitic stalagmite from Lynds Cave, a limestone cave near Mole Creek in northern Tasmania, Australia, has been dated and shows continuous deposition at a uniform rate from 15.0 to 11.7 ka B.P. (ionium dates) or 12.6–8.8 ka B.P. (radiocarbon dates). The age difference obtained by comparing the two dating methods is highly significant and strongly supports recent work by Bard et al. (1990) on Barbados corals.

The speleothem was found to be unsuitable for palaeotemperature estimation by oxygen isotope analysis but the time of deposition is known to have been one of rapidly rising temperatures.

Trace element composition was determined by neutron activation analysis (NAA) for fifteen samples spaced along the stalagmite core. All elements present in measurable quantities showed significant temporal variation in concentrations which are in part believed to be due to environmental change. A significant positive trend in Mg/Sr content and a negative trend in Br content appear to be temperature related. The halide content is shown to be of terrestrial origin.

Introduction

The speleothem, designated LC, was originally collected to test its suitability for isotopic analysis ($^{18}O/^{16}O$) to obtain determinations of palaeotemperature. The specimen was collected from the surface of an alluvial terrace in the main stream passage of Lynds Cave where it had been knocked over by visitors. It was found to be 1002 mm tall. Longitudinal sectioning indicated continuous deposition for the basal 867 mm. At this point there is a significant depositional break with creamy white calcite below and greyish white calcite above. The basal depositional phase has been dated using both ^{14}C and uranium series dating.

Lynds Cave is situated ca. 15 km W of Mole Creek in Northern Tasmania (41°34'20"S, 146°13'40"E) (Fig. 1). The cave system has three entrances near the base of a limestone cliff bordering the eastern bank of the Mersey River at ca. 300 m above sealevel. The host rock is a strongly folded Ordovician limestone of the Gordon Group, a major unit of the Wurawina Supergroup, with a stratigraphic thickness of 1300 m. It is a tropical, marine, predominantly algal limestone deposited under peritidal conditions (Burrett and Goede, 1987).

The geochemistry of the limestone has been examined by Rao (1981) who found that it was characterised by low Mn (25–244 ppm), moderate Na (64-375 ppm) and high Sr (261–1536 ppm) concentrations, similar to modern tropical aragonitic marine carbonates. These trace elements are present in the carbonate fraction. The predominant non-carbonate impurity is the clay mineral illite whose abundance is reflected by the concentrations of the elements Ti and K.

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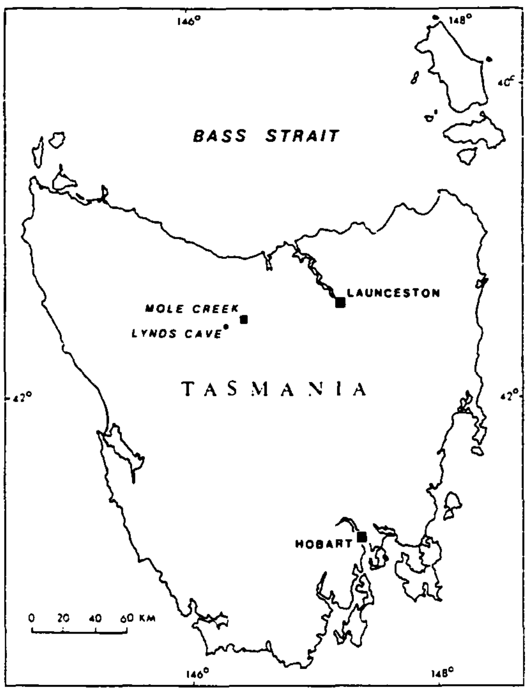

Fig. 1. Locality map showing position of Lynds Cave within Tasmania.

The area near Lynds Cave has a mean annual temperature of 9.5°C and a mean annual precipitation of 1500 mm. The mean annual surface temperature is reflected in the cave temperature measured as 9.5 ± 1°C. Both cave and surface temperatures may have been 6–7°C lower during the late last glacial maximum ca. 18.000 years ago (Colhoun. 1985).

The vegetation of the limestone slopes above the cave consists of wet sclerophyll forest with a rainforest understory (Goede and Hitchman. 1984).

Radiometric dating

Both radiocarbon (^{14}C) and uranium series (^{230}Th ^{234}U) dating methods can be used for the age determination of speleothems. Under favourable conditions ^{14}C-analysis can provide dates (back) to about 50 ka B.P. while thorium uranium isotope analysis is applicable to the past 350 ka. Reliable dates can, however, only be obtained if certain conditions are fulfilled. For both ^{14}C and uranium series dating the sample material must have remained a closed system since the calcium carbonate was precipitated. If the speleothem was porous initially, both ^{14}C and uranium can be added from percolating dripwater at a later stage and the dates obtained would, therefore, be too young. Alternatively, uranium can be leached from porous samples to produce a date that is too old. Since the stalagmite LC consists of dense, compact crystals without any signs of recrystalization, it is not expected to produce problems in this respect.

The ^{14}C dating presents a problem in that the ^{14}C content of the bicarbonate in seepage water from which the calcium carbonate is precipitated, is diluted to a certain extent because the carbon is derived in part from limestone which does not contain ^{14}C (reservoir effect). The exact amount of this dilution is difficult to assess, although some indication can be deduced from the $^{13}C/^{12}C$ ratio. Using the ratio of ESR readings on another stalagmite (LY) from the same cave, on of us (A.G.) concluded that 2160 yr should be subtracted from the apparent ^{14}C dates to obtain the actual radiocarbon ages (Goede and Hitchman, 1984). In the present instance we estimate that the stalagmite LC probably showed an initial age of between 1000 and 2000 yr, so that we subtract 1500 ± 500 yr from dates presented here.

A complication can arise with the uranium-series dates. If the speleothem contains significant amounts of detrital material, it usually introduces thorium, which has the effect of increasing the apparent uranium-series ages and an adjustment becomes necessary. If the $^{230}Th/^{232}Th$ is greater than 16, the correction for the initial age is usually small compared to the statistical uncertainty of the date and the uncertainty of the size of the correction becomes unimportant.

The stalagmite LC has previously been dated by the uranium series method (Goede and Harmon, 1983), but not with sufficient precision to provide an adequate time-scale. The positions of the new samples are shown on Fig. 2 and the results are given in Table 1. It is notable that all three uranium series ages are older than the ^{14}C dates, even before the adjustments discussed above are made. After subtraction of 1500 yr from the ^{14}C dates and subtraction of less than 80 yr from the uranium series ages for the small amount of initial ^{230}Th.

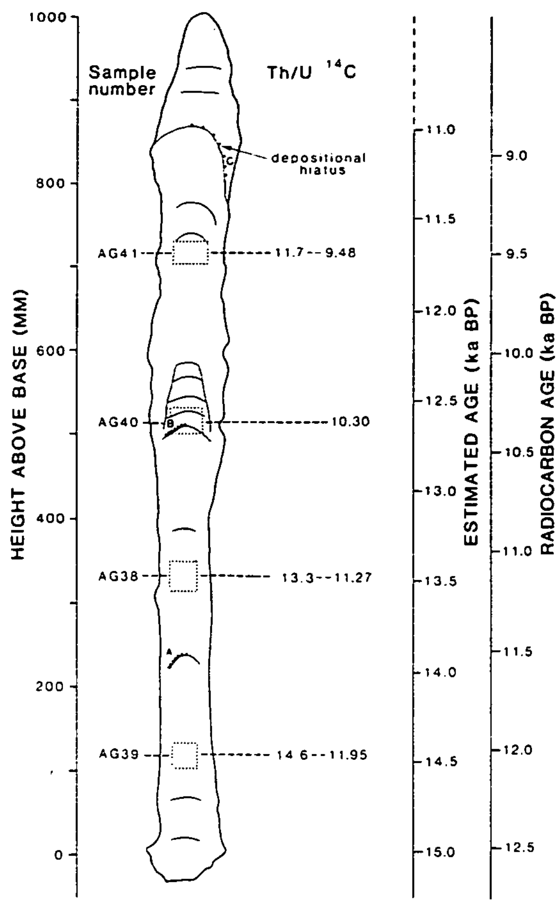

Fig. 2. Longitudinal section of LC stalagmite showing nature of depositional layering and indicating positions sampled for radiometric dating and stable isotope analysis of growth layers. Estimated age is based on ionium dates.

the difference between the two methods is 2300 yr on average. From comparison with dendrochronologically dated wood we already know that ^{14}C dates in the early Holocene are 800–1200 yr too young (cf. *Radiocarbon*, 28, 1986) and during the Late Pleistocene even larger discrepancies have occurred (Vogel, 1983, 1987). The fact that radiocarbon dates between 11.000 and 15.000 yr ago are indeed younger than uranium series ages, by the amounts shown in Table 1, has recently been convincingly confirmed by Bard et al. (1990). Since the time-scale for the past 40 ka is at present still almost universally based on the ^{14}C method (in radiocarbon yr B.P.), we will use the derived ^{14}C dating of the stalagmite in the discussions that follow.

The growth rate of the stalagmite LC appears to be uniform within the limits of precision of radiometric dating at 233 mm per 1000 radiocarbon years, and extrapolation gives a time range of 12.560 yr B.P.–8830 yr B.P. for the basal 867 mm. It thus spans the final stage of rapid warming in the southern hemisphere after the Last Glacial Maximum at 18.000 yr B.P. As mentioned above, there can be a systematic error of up to 500 yr in these figures as a result of the uncertainty in the magnitude of the reservoir effect.

Correlation, regression analysis of the corrected Th/U ages vs medium sample height above base yields a growth rate of 215 mm per 1000 years. Extrapolation suggests a time range of 15.0–11.0 ka B.P. This is regarded as a more reliable estimate of the true time period of stalagmite growth. It is used to provide an alternative time scale for temporal variations in trace element concentrations (Figs. 2 and 4).

Sampling techniques

The stalagmite was cut longitudinally into two more or less equal halves. Pieces of one were set in plaster and small samples for isotope analysis drilled from the core at regular intervals. The other half was cut up to provide core samples of between 35 and 50 g for radiometric dating. Five mm thick horizontal slices weighing between 8 and 10 g for chemical analysis were also cut from this half. They were then crushed and homogenized before being analysed.

Isotope analysis

The $^{18}O/^{16}O$ ratio of calcite in speleothems can be used to make estimates of palaeotemperatures, but only if precipitation has taken place under conditions of isotope equilibrium. Oxygen isotope equilibrium may be upset by evaporation of dripwater during deposition or by rapid loss of CO_2 from the depositing solution to the cave atmosphere due to aeration. The collecting site was in the main stream passage where strong air currents, that would encourage some evaporation, have been observed.

Two tests have been suggested by Hendy and

TABLE I

Radiometric analyses of stalagmite LC

	AG 39	AG 38	AG 40	AG 41
Radiocarbon analyses				
Anal. no.	Pta-3708	Pta-3707	Pta-3791	Pta-3792
Median height above base (mm)	120	334	515	717
^{13}C (‰)	−9.9	−8.4	−8.4	−9.0
Apparent age (yr B.P.)	13.450±130	12.770±100	11.800±100	10.980±110
Corrected age (yr B.P.)	11.950	11.270	10.300	9480
Uranium series analyses				
Anal. no.	U-294	U-293		U-305
U-content (ppm)	0.305	0.262		0.307
$^{234}U/^{238}U$	2.85±0.04	2.97±0.03		3.12±0.03
$^{230}Th/^{232}Th$	442	236		171
$^{230}Th/^{234}U$	0.128±0.003	0.117±0.003		0.104±0.004
Apparent age (yr)	14.600±420	13.350±360		11.800±500
Corrected age* (yr)	14.570	13.330		11.740

*Assuming Initial $^{230}Th/^{232}Th = 1$

Wilson (1968) to determine if deposition has taken place under conditions of oxygen isotope equilibrium. This requires determinations of both $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios which are usually expressed as values in ‰ relative to the PDB (Pedee Belemnite) standard for calcite.

Four Tasmanian stalagmites have so far been found to have been deposited under conditions of oxygen isotope equilibrium, including one from Lynds Cave, and palaeotemperature curves have been published (Goede and Hitchman, 1984; Goede et al., 1986; Goede et al., 1990). The present-day oxygen isotope value for calcite deposited under equilibrium conditions in Lynds Cave has been determined as −4.1‰ $\delta^{18}O$ at a present-day temperature of 9.5°C (Goede and Hitchman, 1984). Unusually in Tasmania $\delta^{18}O$ values have a positive relationship to temperature (Goede et al; 1986, 1990). Under full glacial conditions a value of −6.0‰ $\delta^{18}O$ has been determined associated with a mean anual temperature lowering of up to 6°C (Goede et al. 1990)

Hendy and Wilson's first test requires analysis of samples taken at regular intervals along the core of the stalagmite. If a strong positive correlation is found between the $\delta^{18}O$ and $\delta^{13}C$ values of samples, the ^{18}O values cannot be used as indicators of palaeotemperature. Forty-four paired values yielded $r = 0.730$ ($t = 6.9303$), a highly significant positive correlation.

The actual $\delta^{18}O$ values range from −3.96 to −2.99‰ with a mean of 3.58‰ while ^{13}C varies between −10.09 and −5.56 with a mean of −8.79‰.

The range of $\delta^{18}O$ values observed lies largely outside the range of values found for Tasmanian cave calcite deposited under oxygen isotope equilibrium conditions (−3.75 to −6.00‰) suggesting that significant fractionation had already taken place when the drip water reached the tip of the stalagmite. If deposition had occurred under conditions of oxygen isotope equilibrium one would also have expected a time related trend of $\delta^{18}O$ values becoming isotopically heavier with increasing height above base since the period of deposition is known to have been one of rapidly rising temperatures. No such trend can be observed in the data.

In the second test multiple samples are taken at intervals along a single growth layer. If analyses show a progressive trend towards heavier isotopic values for both $\delta^{18}O$ and $\delta^{13}C$, isotopic fractionation is again demonstrated. Seven samples were taken from each of three growth layers (*A*, *B* and *C* in Fig. 2) and $\delta^{18}O$ and $\delta^{13}C$ values determined. Details of sample preparation and instrumentation used are given in Goede et al. (1990). Two growth layers (*B* and *C*) showed a significant trend towards isotopically heavier $\delta^{18}O$ values and all three showed such a trend for $\delta^{13}C$ values (Fig. 3).

The two tests show conclusively that $\delta^{18}O$ values determined for the LC stalagmite cannot be used as indicators of palaeotemperature.

Chemical analysis

Chemical analysis of trace elements in speleothems has not received much attention in the spelaeological literature. Most of the work done has been concerned with explaining the occurrence of coloured speleothems (Jakucs, 1961; White 1976; Caldwell et al., 1982). However, many impurities do not affect the normally white colour of calcite and their presence has been neglected by those primarily interested in explaining variations in colour.

We are more interested in the possibility that the concentration of certain trace elements incorporated in calcite speleothems may vary over time due to the influence of environmental changes.

Several authors (Katz, 1973; Fuchtbauer and Hardy, 1976; Gascoyne, 1983) have shown that the homogeneous distribution coefficient of magnesium (D_{Mg}) over a temperature range of 5–90°C bears a positive relationship to temperature. Of particular interest is the study of Gascoyne (1983)

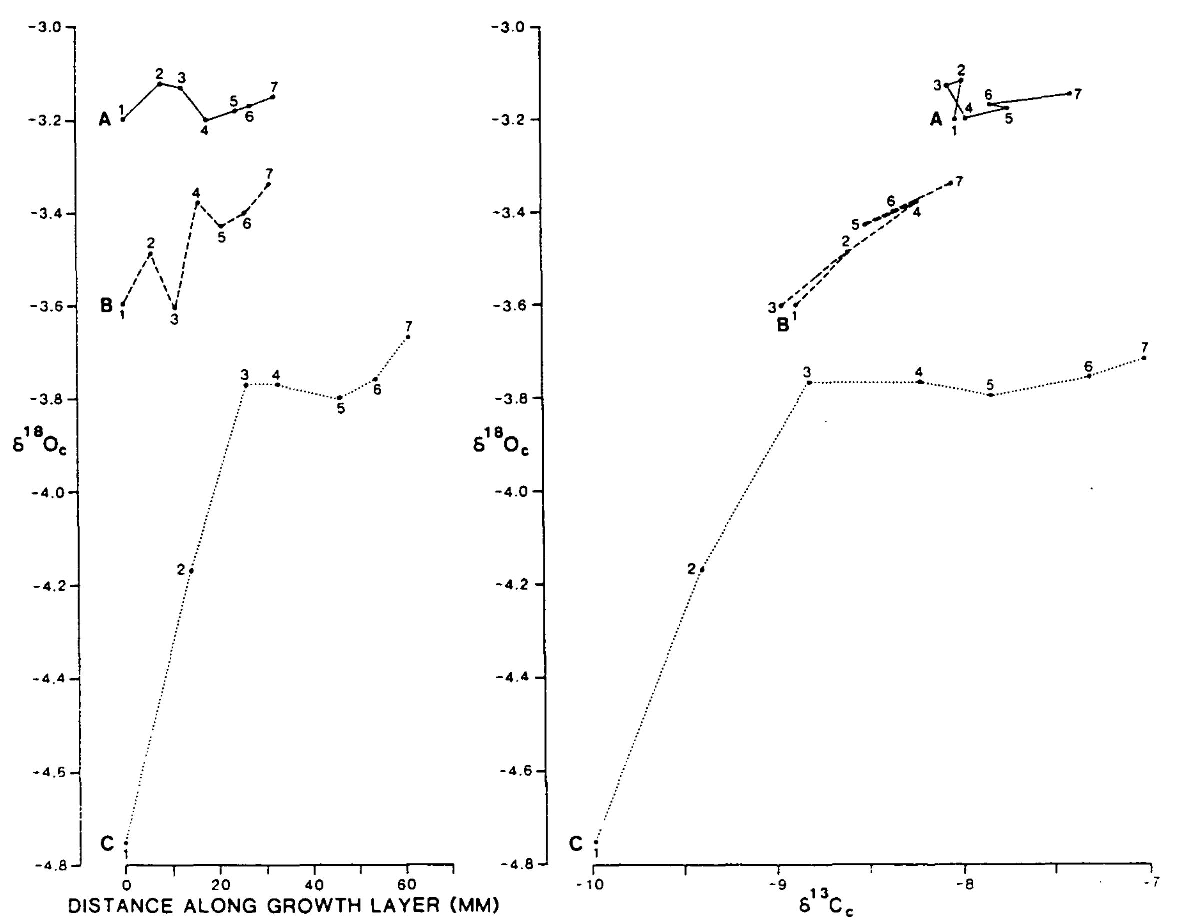

Fig. 3. Trends in $\delta^{18}O$ values with distance (left) and with $\delta^{13}C$ values (right) along each of the three growth layers indicated in Fig. 2.

who compared the distribution coefficients of magnesium between temperate (7°C) and tropical (23°C) cave sites and obtained average D_{Mg} values of 0.017 and 0.045 respectively. His results indicated that the Mg content varied directly with temperature and "in a sufficiently pronounced manner that a 1°C rise in depositional temperature of a speleothem containing 500 ppm Mg, at ~10°C, would be seen as an increase of ~35 ppm Mg—a readily determinable shift". In contrast, he found that the distribution coefficient for Sr showed no apparent relationship to seepage temperature. The D_{Mg} values appeared to be little affected by variations in the Mg/Ca ratio, at least within the range 0.02–0.53, or by the degree of saturation of the dripwaters.

Chivas et al. (1986) studied the magnesium content of non-marine calcitic ostracod shells and found it to be a function of both temperature and salinity. At 3‰ salinity they found that the atomic Mg/Ca ratios of the shells increased from approx. 0.015 at 10°C to 0.038 at 25°C. Like Gascoyne, they found that Sr uptake is directly related to the Sr/Ca ratio of the water, with little or no temperature effect over the range 10–25°C. De Deckker et al. (1988) used Mg/Ca and Sr/Ca ratios of ostracod shells from cores of palaeolake sediments from the Gulf of Carpentaria to deduce changing palaeo-environmental conditions from 40.000 to 13.000 ka B.P.

It appears from these and other studies that the concentrations of both Mg and Sr in water, and consequently in any calcite deposited from it, may vary markedly with salinity, but while the Mg content of calcite is strongly influenced by temperature the Sr content is not. Variations in magnesium content in speleothem calcite therefore may reflect both temperature and salinity changes. The possible effects of temporal changes in drip water salinity may be reduced by using variations in the Mg/Sr ratio rather than Mg content as an indicator of palaeotemperature change.

For this study, fifteen samples spaced along the growth axis of the stalagmite core were submitted to the CSIRO Division of Energy Chemistry for neutron activation analysis (NAA). Analysis revealed that some thirteen trace elements were present in sufficient amounts for quantitative measurement in all, or nearly all, samples. All elements showed significant variations in concentration with time along the growth axis of the speleothem. The highest and lowest values and their standard deviations are shown in Table 2.

Measurement precision varies widely between elements. It is poor for Mg and Sr. Because of the possible significance of these two elements in calculating a palaeotemperature index, their analyses were repeated using atomic absorption spectrophotometry (AAS) which provided a much higher level of analytical precision (ca. 2%). In the data analysis that follows, the AAS analyses for Mg and Sr are used together with the NAA analyses of the other elements.

In order to better understand the nature of variation in trace elements, the first step was to produce a similarity matrix to gain an indication of the extent to which different trace elements covaried in their abundance. The matrix shows many statistically significant relationships, both positive and negative. By treating the trace elements as OTU's (observed taxonomic units) a clustering procedure was applied to the matrix by average linkage using the pair group method first

TABLE 2

Highest and lowest concentrations in ppm of trace elements found in NAA and AAS analysis of LC stalagmite samples

Element	Highest value	Lowest value	No. of analyses
Neutron Activation Analysis (NAA)			
Na	87.8 ± 4.4	31.5 ± 1.9	15
Mg	4000 ± 1300	1300 ± 800	15
Cr	9.61 ± 0.48	3.82 ± 0.40	15
Fe	145 ± 15	40 ± 12	15
Co	0.085 ± 0.017	0.027 ± 0.017	10
Zn	124 ± 37	13.1 ± 3.8	15
Sr	253 ± 46	128 ± 42	15
Ba	77 ± 16	31.6 ± 7.5	15
Sc	0.0855 ± 0.0045	0.0335 ± 0.0022	15
Br	1.16 ± 0.08	0.24 ± 0.11	13
La	0.083 ± 0.016	0.045 ± 0.013	11
Au	0.0613 ± 0.0031	0.0056 ± 0.00066	15
U	0.66 ± 0.12	0.25 ± 0.096	12
Atomic Absorption Spectrophotometry (AAS) (measurement precision ca. 2%)			
Mg	3833	1813	14
Sr	252	153	14

proposed by Sokal and Michener (1958). The technique is discussed in detail in Sokal and Sneath (1963). The clustering procedure takes into account the magnitude but not the sign of the similarity coefficient. The dendrogram is shown in Fig. 4.

Four groups are clearly identified at a 95% level of significance. Group I contains the alkaline earth metals Mg, Sr and Ba bearing a strong positive similarity to each other. But it also includes Br which has a strong negative relationship to the other three. The second group contains Na, Sc, La and U, while the third group includes the metals Co, Cr, Fe and Au. Group IV contains only one element, Zn, which does not show a significant similarity to any other element except Co.

It has been suggested that traces of Br and Cl in speleothem calcite might be of marine origin and that this could be tested by determining the Br Cl ratio and comparing it with that of seawater given as 0.00348 (Millero, 1974). For the three LC samples with the highest Br content the Cl concentration was determined by ion chromatography. The Br/Cl ratios obtained ranged from 0.1289 to 0.2225.

For comparison similar analyses were also carried out on a 19,000 yr old stalagmite from a fossil sea cave (Blister Cave) on the west coast of King Island, located off the NW tip of Tasmania (Goede et al., 1979). The continental shelf seaward of this site is quite narrow so that, with prevailing westerly winds, Blister Cave has always been subject to a strong marine influence. Br and especially Cl concentrations were much higher than in the LC stalagmite (Br: 8.36 ± 0.63 and Cl: 4320 ± 220 ppm). The Br/Cl ratio of 0.0049 is not significantly different from the seawater ratio.

The halide content of the LC stalagmite is clearly not derived from a marine source. This is also supported by the trend towards lower Br concentrations over a period when sealevel was rising rapidly ((Bard et al., 1990) and Bass Strait was being flooded bringing Lynds Cave significantly closer to a marine source.

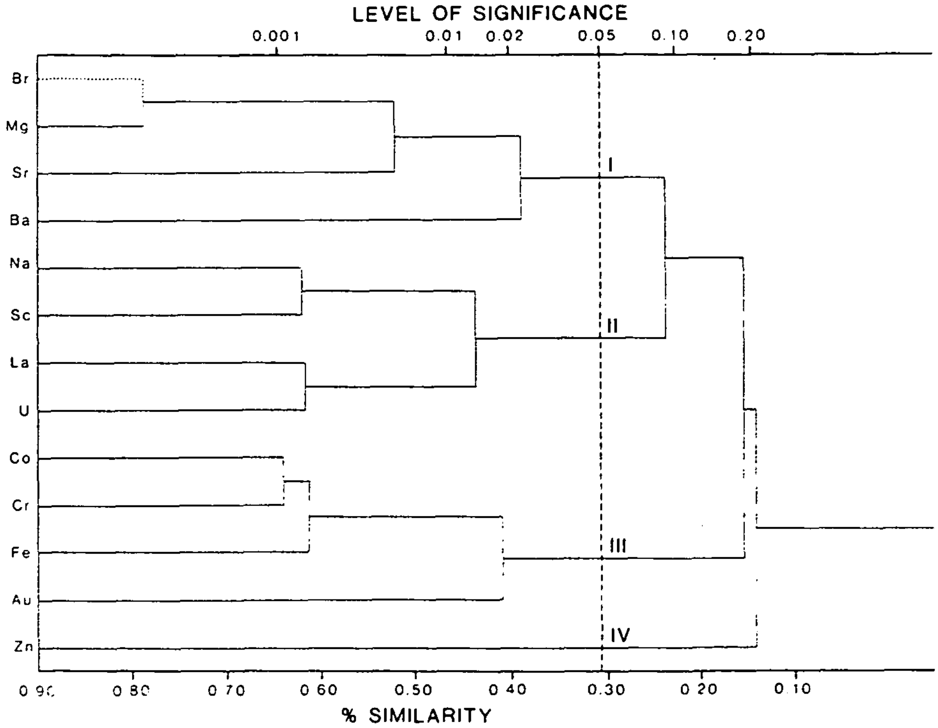

Fig. 4. Dendrogram showing degree of similarity of chemical behaviour for the thirteen trace elements whose concentrations were determined. At the 0.05 level of significance four groups, labelled I–IV can be distinguished

Discussion

Age determination

Both ^{14}C and Th/U analyses indicate that the main part of the LC stalagmite grew at a uniform rate, a character it shares with many other uniform diameter stalagmites. This is a useful characteristic because it allows correlation, regression analysis of medium sample height vs age to provide a linear timescale.

It is not the first time that a systematic age discrepancy has been found when speleothems have been dated by these two methods. A 2800 mm tall stalagmite from Cango Cave, Southern Africa, was dated by one of us (Vogel, 1983) in a similar manner. It contained a major growth hiatus with the upper 950 mm of the stalagmite having formed during the past 6000 years. In this part there was excellent agreement between the two dating methods when the usual corrections were made. The lower part of the speleothem is Late Pleistocene in age and the ionium dates indicate a uniform growth rate of 62 mm/ka between 39,000 and 18,000 ka B.P. For much of this period ^{14}C dates were substantially younger than the corresponding ionium dates.

The difference was explained by variations in the ^{14}C concentrations of the atmosphere brought about by variations in the intensities of the earth's magnetic field. The dates presented here indicate that a substantial difference between the two timescales remains until at least 10,000 ka B.P. with an average age difference of 2300 yr between 15 and 10 ka. Similar differences have been demonstrated by Bard et al. (1990) in their age determinations of Barbados corals. Some of the implications for archaeology have been discussed by Vogel (1987).

Isotopic data

Analyses of ^{18}O and ^{13}C values and the application of the tests first suggested by Hendy and Wilson (1968) make it clear that the stalagmite was not deposited under conditions of oxygen isotope equilibrium and that consequently $\delta^{18}O$ values cannot be used to indicate variations in palaeo-temperature. This is unfortunate as it means that such values cannot be used to test the possibility that some of the temporal changes in trace element composition are related to changes in palaeotemperature.

Trace elements

In considering the significance of trace element variations it must be appreciated that trace elements may be present in calcite in at least five different modes of occurrence (Gascoyne, 1983).

(1) The inclusion of particulate detrital matter at interstices between growing crystals. The main detrital impurities are likely to be clay minerals.

(2) Trace elements may be absorbed onto the surface of growing crystals.

(3) Trace elements are introduced by direct substitution for Ca^{2+} ions in the calcite lattice.

(4) Trace elements may be introduced as part of organic complexes derived either from organic impurities in the limestone or from the soil overlying the limestone by downward leaching.

(5) Some elements, especially halides, may be concentrated in fluid inclusions.

Chemical impurities due to detrital contamination are well known from studies of ice cores in Greenland and Antarctica (Bradley, 1985; Miklishankiy et al., 1980). Such contamination causes an enrichment in a number of characteristic elements which include Mg and Fe. In a detritally contaminated stalagmite one expects to find a positive correlation between Mg and Fe content. The lack of such correlation indicates that detrital contamination of our samples is not significant. A negligible level of detrital contamination is also indicated by the high values of $^{230}Th/^{232}Th$ ratios for the three uranium series analyses.

Any organic content also appears to be very low. A high organic content (esp. humic and fulvic acids) imparts a dark colour to speleothems and our material shows no evidence of this. Electron spin resonance (ESR) spectrographs were made of all fifteen samples analysed here and none show peaks that can be attributed to the presence of organic radicals that are known to affect calcite ESR spectra by their presence (De Canniere et al., 1985).

The situation appears to be one where we are dealing with a relatively simple system where the chemical processes mentioned in (2) and (3) and possibly (5) are predominantly responsible for variations in trace element composition.

Although temporal trace element variations in speleothems appear to have received little attention, a considerable body of literature is available on such variations in both freshwater and marine shell as well as in carbonate rocks. The available literature suggests that, in both chemical and biochemical systems, the magnesium content of carbonate rocks and fossil shells is strongly influenced by temperature as well as salinity, whereas strontium variations are relatively insensitive to temperature changes but are predominantly related to salinity variations of the solution from which carbonates are deposited (Gascoyne, 1983; Chivas et al., 1986).

The problem is to assess the extent to which variations in trace element composition are linked to temperature changes since $^{18}O/^{16}O$ ratios in the LC stalagmite cannot be used as palaeotemperature indicators. However, there is widespread evidence that the time period over which the basal 867 mm of LC were deposited was marked worldwide by rapid deglaciation and, particularly in the Southern Hemisphere, by rapidly rising temperatures (Lorius et al., 1985).

Any trace element whose concentration is strongly temperature dependent can be expected to show either a strong positive or negative correlation with time. Since the stalagmite has grown at a uniform rate, a similar correlation should also occur with position of the sample above the base of the stalagmite.

Since Mg is known to be influenced by depositional temperatures, the four elements of group I are most likely to show some temperature control. These four and the ratio Mg/Sr were correlated with sample height above stalagmite base and the following values of r obtained: Br (0.923), Mg (0.802), Sr (0.569) and Ba (0.645). Since it has been suggested that Mg/Sr is a better indicator of palaeotemperature changes than Mg, it was also correlated with height above base. For Mg/Sr the correlation coefficient is $r = 0.849$. This clearly indicates that variations in Br, Mg/Sr and Mg may have potential as palaeotemperature indicators (Fig. 5).

Variations in Na and those elements whose concentrations show significant covariance with this element (Sr, Sc, La and U) may indicate variations in dripwater salinity. At an inland site such as Lynds Cave represents, they may indicate variations in evaporative effects.

It is not clear what environmental influences affect variations in Co, Cr, Fe and Au. Variations in the first three elements are particularly closely related.

The variation in Zn concentration shows a significant correlation only with Co. Tsusue and Holland (1966) found some evidence that the distribution coefficient of zinc with calcite increased rapidly towards lower temperatures but they were looking at a temperature range of 50–250°C. In this study it appears that temperature variations are not a significant factor.

Conclusions

This preliminary study gives strong support to the concept that variations in trace element composition in speleothems can be used to gain palaeoenvironmental information.

Because the LC stalagmite is known to have formed at a time of rapidly rising temperatures, the extent to which variations in trace element concentrations or ratios are sensitive to temperature change can be assessed. It is suggested that the Mg/Sr ratio may be used as an indicator of temperature change.

The presence of measurable concentrations of Br and their apparent strong negative relationship to temperature changes is a complete surprise. Bromine and chlorine are clearly not of marine origin. However, the very high Cl content of the Blister Cave stalagmite compared with the LC material (4–9 ppm) indicates that temporal Cl variation in speleothems found in caves in coastal areas may be a sensitive indicator of sealevel change especially where a wide continental shelf with a gentle off-shore gradient causes marked lateral displacement of the shoreline.

The next stage of research will be to examine a

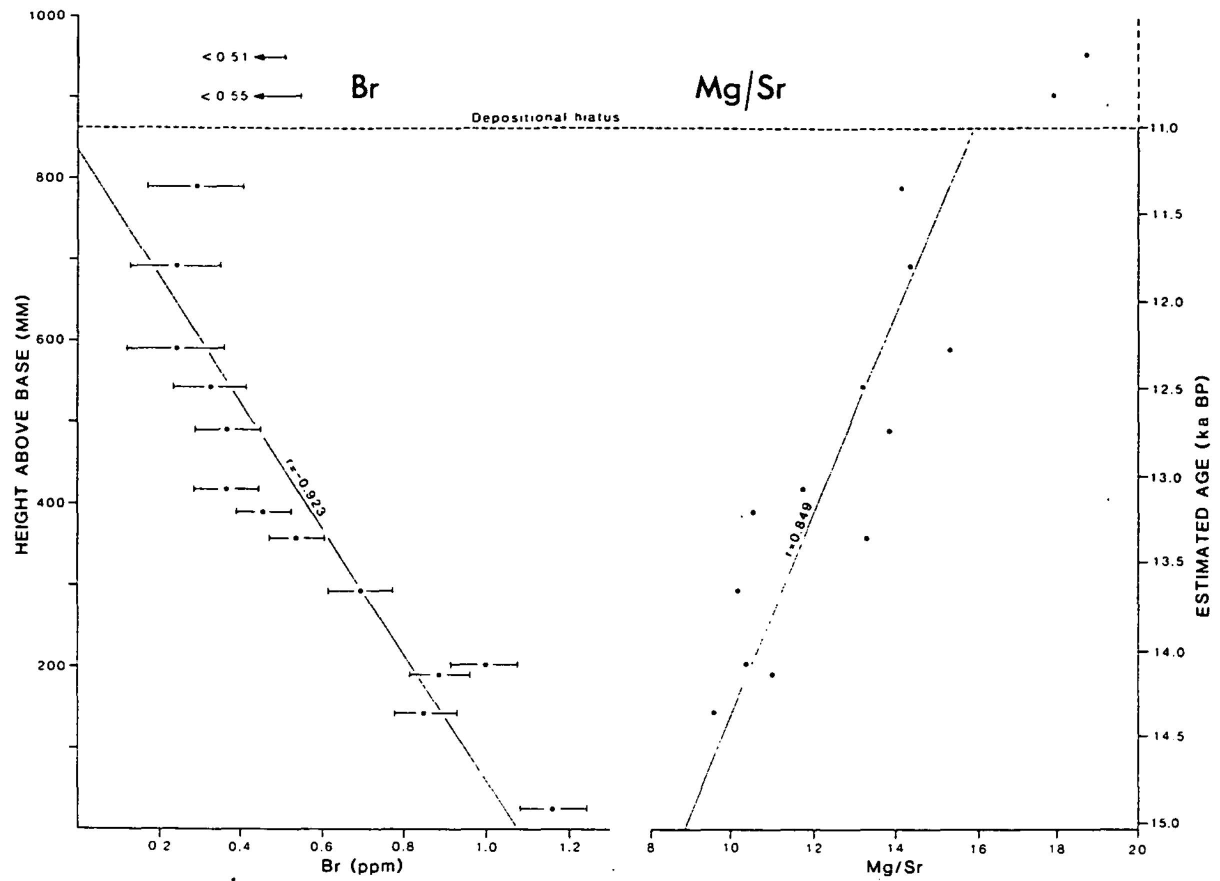

Fig. 5. Relationships of sample heights (H) in mm above base of stalagmite with Br concentrations and Mg Sr ratios. Regression lines and correlation coefficients are shown. In both relationships the correlation is highly significant (level of significance <0.001). Estimated age is based on ionium dates.

well dated speleothem deposited over a much longer time span and under conditions of oxygen isotope equilibrium so that close comparisons can be made not only with the patterns of $^{18}O/^{16}O$ within the same stalagmite but also with palaeotemperature curves from other sources.

Speleothem studies have the potential to shed much light on the patterns of temperature changes and other environmental changes (e.g salinity, vegetation cover) in extra-glacial terrestrial environments. Such studies become even more attractive with the prospect of greatly improved precision in uranium-series dating of speleothems with the recent introduction of isotope-dilution mass spectrometry (Li et al., 1989).

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TASMANIAN SPELEOTHEMS : PROGRESS AND PROSPECTS FOR PALAEOENVIRONMENT RECONSTRUCTIONS

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INTRODUCTION

The recent paper by Francey and Cook in *Quaternary Australasia* Vol. 8, no. 2 made it obvious that many Quaternarists are not familiar with the palaeoenvironmental studies of calcite stalagmites in Tasmania that have been in progress since 1979. The research is reaching a stage where very detailed information may be obtained about environmental change, which clearly has considerable value for comparison with similar information from other sources, e.g. Tasmanian tree rings.

PAST RESEARCH

The project commenced in 1979 with the collection of monthly precipitation and cave drip samples for stable isotope analysis ($^{18}O/^{16}O$), D/H) from three sites. The sites were located in major karst areas known to contain speleothem material suitable for analysis. The isotope values and their seasonal variations were reported by Goede et al. 1982.

Speleothem material suitable for isotopic analysis consists of uniform diameter stalagmites which tend to grow continuously over time periods ranging from 10^3 to 10^5 years at a uniform long term rate. Longitudinal sectioning reveals a layered structure with cuspate layers that are normally convex upwards.

One half of the stalagmite is set in plaster. It is used for the drilling out of small samples for isotope and electron spin resonance (ESR) analysis. The other half is cut up to provide larger core samples for radiometric dating ($^{230}Th/^{234}U$, ^{14}C).

During 1979-81 seven calcitic stalagmites were collected from four different caves. Age determination was carried out by radiometric dating of multiple core samples. Details of the location, physical nature, dating techniques and average growth rate of each specimen are shown in Table 1.

Table 1 - Location, height, age ranges and growth rates of Tasmanian uniform diameter stalagmites.

Code	*Cave Name*	*Area*	*Height (mm)*	*No. of dates* Th/U	14C	*Age Range (ka BP)*	*Growth Rate (mm ka)*	*Oxygen Isotope* Equilibrium
KK	Kubla Khan	MC	1070	8	-	127 - 97	36	No
LT	Little Trimmer	MC	1420	7	-	109 - 76	43	Yes
LX	Little Trimmer	MC	550	3	-	95 - 69	21	No
LY (l)	Lynds Cave	MC	1180	1	4	12.6 - 8.1	262	Yes
LY (u)	Lynds Cave	MC	800	-	3	6.9 - 2.8	200	Yes
LC	Lynds Cave	MC	867	3	4	15 - 11	215	No
FC	Frankcombe C.	JF	720	-	5	4.3 - 2.9	500	Yes
FT	Frankcombe C.	JF	860	3	1	98 - 55	20	Yes

Area codes : MC - Mole Creek; JF - Junee Florentine

PALAEOENVIRONMENTAL INFORMATION

Both $^{18}O/^{16}O$ and $^{13}C/^{12}C$ isotope measurements can provide useful information about palaeoenvironmental conditions as long as deposition of calcite takes place under conditions of isotope equilibrium (Hendy & Wilson, 1968). Sometimes equilibrium is not maintained due to rapid degassing of CO_2 or to partial evaporation of drip waters during deposition.

Oxygen Isotope Ratios $^{18}O/^{16}O$ changes in calcite reflect variations in cave temperature. The present day value of the ratio is determined for each cave site by sampling the tips of a number of active, rapidly growing straw stalactites (Goede et al., 1982; Goede & Hitchman, 1984). If the isotopic composition of drip water has been determined and the cave temperature has been measured it is also possible to calculate a theoretical value for the ratio.

The ratio is controlled by two opposing effects : the temperature of the cave site and the mean isotopic composition of the drip water. Temperatures in most karst caves show little seasonal variation ($<1^{0}C$) and usually approximate closely to the mean annual temperature above ground. If the mean annual surface temperature changes the cave temperature will adjust accordingly.

Taking the example of a fall in temperature it is found that two opposing processes come into play.

1.A fall in cave temperature will cause a larger proportion of the heavier ^{18}O isotope to be incorporated into the calcite being deposited. This would cause the value of the $^{18}O/^{16}O$ ratio to increase.

2.The fall in surface temperature will cause the $^{18}O/^{16}O$ composition of precipitation to become isotopically lighter causing a similar effect in cave drip water. This would cause the value of the $^{18}O/^{16}O$ in the calcite to decrease.

Whether $^{18}O/^{16}O$ ratios in speleothem calcite have a positive or negative relationship to temperature depends on which of the two opposing processes has the larger effect. In most parts of the world where speleothems have been analysed the first process appears to dominate and $^{18}O/^{16}O$ ratios bear a negative relationship to temperature. The two well documented exceptions are found in Vancouver Island and Tasmania where the relationship has been shown to be a positive one (Gascoyne et al., 1981; Goede et al. 1986; Goede et al. 1990). Model isotope values for Mole Creek are shown in Fig. 1.

Tasmania appears to have experienced an unusually large glacial-interglacial shift in the isotopic composition of precipitation. The most likely explanation is a marked poleward shift in the oceanic moisture source under glacial conditions associated with strong latitudinal airflow patterns. Under the present (interglacial) regime it receives much of its moisture supply from tropical sources.

Palaeotemperature curves based on $^{18}O/^{16}O$ ratios have been published for four Tasmanian speleothems and have given valuable information about the timing and magnitude of past temperature changes (Goede & Hitchman, 1984; Goede et al. 1986; Goede et al. 1990).

Carbon Isotope Ratios They are more difficult to interpret. If no fractionation occurs during deposition they should appear to be closely related to the nature of the vegetation cover. Soil CO_2 plays a dominant role in the solution of limestone by seepage water because of its high concentration. It is depleted in ^{13}C ($-27‰<\partial^{13}C<-13‰$ vs PDB) giving rise to isotopically light calcite.

Groups of plants have different biochemical pathways for their photosynthetic processes (C_3, C_4 and CAM metabolisms) leading to different fractionation effects (Smith & Epstein. 1976). The isotopically lightest values in calcite ($\partial^{13}C<-10‰$) may be associated with moist forest vegetation rich in C_3 plants, heavier values ($-10‰<\partial^{13}C<-8‰$) may be associated with a vegetation dominated by grasses (C_4 plants). Limited deposition of calcite can take place with little or no contribution of biogenic CO_2 ($\partial^{13}C>8‰$). See Goede et al. (1990) for a possible example.

Variations in the $^{13}C/^{12}C$ values of Tasmanian stalagmites studied so far are clearly not random but show little relationship to $^{18}O/^{16}O$ variations even during major climatic transitions. In some stalagmites there is a strong correlation between $d^{13}C$ and uranium content (Goede, 1989) which may suggest that variations in the amount of organic impurities are responsible.

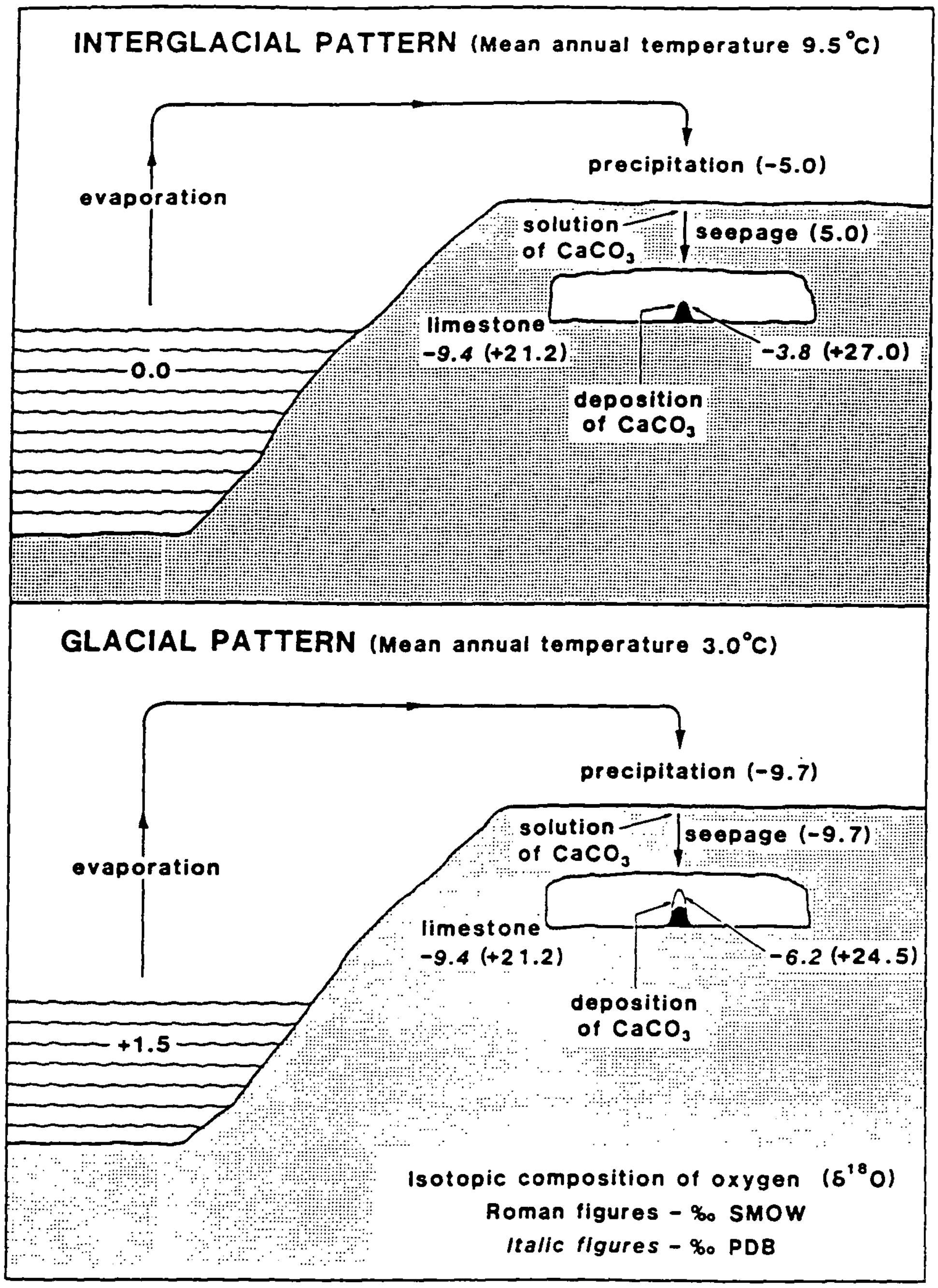

Figure 1 - Model of oxygen isotope composition of precipitation and cave calcite for both interglacial (present day) and glacial conditions based on research in caves at Mole Creek, Tasmania.

All terrestrial figures, except the mean values of precipitation and seepage at the glacial maximum, have been obtained by laboratory measurement of samples collected in the field. The two glacial maximum values can be calculated since mean annual temperature can be estimated from other information sources (Colhoun, 1985), the isotopic composition of the calcite has been measured and the fractionation effects of calcite deposition are well known (Friedman & O'Neil, 1977). The mean isotopic composition of ocean water is equated with the SMOW standard and the change for full glacial conditions has been estimated from isotope studies of deep sea cores (Hays et al., 1976).

Deuterium Hydrogen Ratios They are determined on fluid inclusion water after its extraction from a calcite sample. Before being measured the water has to be converted to hydrogen using techniques first published by Schwarcz et al. in 1976.

Since D/H ratios of mean annual precipitation are temperature dependant they are influenced by changes in climatic conditions. Values should correlate with $^{18}0/^{16}0$ in calcite which are also temperature dependent (Goede et al., 1986). In theory D/H values can be used to reconstruct the $^{18}0/^{16}0$ values of drip water from the same stratigraphic horizon because in meteoric water there is a close statistical relationship between the two (meteoric water line). The $^{18}0/^{16}0$ ratios of drip water can then be used to calculate the $^{18}0/^{16}0$ of calcite deposited from the water at different temperatures since the fractionation effect between the water and the calcite deposited from it is well known.

Considerable efforts have been made to determine reliable D/H ratios from fluid inclusion water. However, due to the very small quantities of water involved and the complexity of the extraction procedure and conversion of the sample to hydrogen the analyses were found to have a low degree of reproducibility. The results tend to give a qualitative indication of temperature only. For an example see Goede et al. (1990).

Trace Element Variations Recent work (Goede & Vogel, in press) on one Tasmanian stalagmite (LC) has demonstrated that many trace elements exhibit significant variations over time and that they are not random but show trends or cyclic patterns probably related to aspects of environmental change. The LC stalagmite has been deposited from 15 to 11 ka BP, a period known to be one of rapid warming. Magnesium and bromium are two elements that show significant trends over the period, as does the ratio Mg/Sr. This suggests that these values may be temperature related. Variations in sodium may indicate variations in dripwater salinity which in turn may reflect variations in rainfall amounts and evaporative effects at the surface.

Electron Spin Resonance ESR spectra of powdered speleothem calcite contain several peaks - their presence, size and sensitivity to gamma radiation can be related to some organic and inorganic inpurities (Hennig & Grün, 1984; Smith et al., 1985).

In the case of the LC stalagmite the sensitivity to gamma radiation of one of the peaks (g value = 2.0005) shows highly significant correlations with Br and Mg concentrations. It suggests that it may be usable as a surrogate variable for temperature changes. Peak intensity is much more easily measured than sensitivity to gamma rays. The disadvantage is that peak intensity is also dependant on the radioactive content of the sample (principally its uranium content) and the age of the sample.

An age correction is easily made for each peak intensity value (Fig. 2), while in this case variations in uranium content can be disregarded as the content and the range of variation are quite low.

The peak intensity is rapidly measured in powdered samples drilled from the stalagmite core at approximately 100 year intervals. All values were adjusted to an age of 11 ka and are plotted in Fig. 2. The Mg/Sr values are also illustrated. Both variables show a significant increase over time which is believed to be largely temperature related.

Because of the ease of sample preparation and the rapidity of measurement of peak intensity, a detailed curve is readily obtained. Figure 2 shows a cool period lasting about 500 years at a radiocarbon age of 11.5 ka BP (cf evidence from Chile in Heusser, 1989) while another cold period appears to have occurred at a radiocarbon age of 9 ka BP.

PROSPECTS FOR FURTHER RESEARCH

Interest in palaeotemperature determinations from speleothems has declined in recent years because of :

1. The difficulty of matching isotope records obtained by discontinuous sampling.
2. Problems associated with establishing deposition under conditions of isotopic equilibrium.
3. Availability of suitable material due to the growth of the conservation movement and a dawning of environmental ethics amongst researchers.

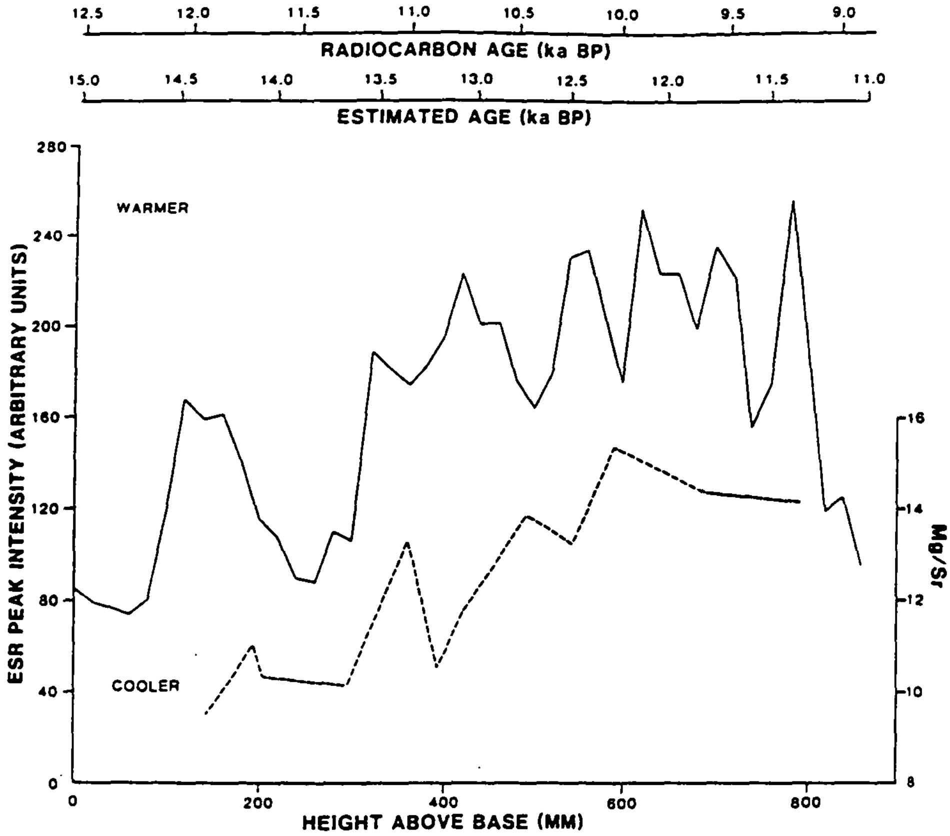

Figure 2 - Profile of age adjusted ESR peak intensities (g value = 2.0005) for LC stalagmite. Increasing intensities are believed to be associated with higher temperatures. Also shown is trend for Mg/Sr ratio which is also believed to be temperature dependent.

However, a number of recent developments make it imperative that stalagmites be re-examined as source of palaeoenvironmental information.

1. Many stalagmites appear to have grown continuously at a uniform rate over tens of thousands of years (see Table 1) and some at least have growth rates of 200-500 mm/ka allowing the possibility of a very high level of temporal discrimination.
2. Speleothem calcite, like coral, is a reliable material for uranium series dating. With recent advances made in mass spectrometry techniques (Bard et al., 1990) very high precision uranium-thorium ages can be obtained. This has also allowed calibration of ^{14}C dates beyond the range of treering chronologies.
3. A new generation of automated stable isotope mass spectrometers makes it much cheaper and quicker to process large numbers of samples for $^{18}O/^{16}O$ and $^{13}C/^{12}C$ determinations. Instead of sampling at intervals it is now practical to carry out continuous sampling on stalagmites. This should make matching of isotope curves much easier, not only between stalagmites, but also with other isotopic records, e.g. those obtained from ice cores and three ring sequences.
4. A recognition that trace element variations sampled along the axis of a stalagmite are not random but appear to be related to environmental changes such as temperature, salinity and vegetation (Goede, 1989; Goede & Vogel, submitted).

5. The discovery that some peak characteristics of ESR spectra are closely related to trace element variations and can be used to sample stalagmites either continuously or at very close time intervals.

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A GIANT LATE PLEISTOCENE HALITE SPELEOTHEM FROM WEBBS CAVE, NULLARBOR PLAIN, SOUTHEASTERN WESTERN AUSTRALIA

Albert Goede, Tim C. Atkinson and Peter J. Rowe

Abstract

A giant halite stalagmite found in a broken condition, and believed to be the tallest recorded anywhere in the world, was collected from Webbs Cave in the Mundrabilla area of the Nullarbor Plain. Reconstruction by fitting together the major fragments showed that it had been 2780 mm tall. Its collapse was due to water percolating down the side and dissolving a cylindrical hole near the base. Uranium series dating proved to be extremely difficult due to the exceedingly low uranium content (2 μg kg $^{-1}$). Analysis of a bulk sample indicates late Pleistocene deposition between 20 and 37 ka. Previous dating of a small halite speleothem from Webbs Cave has shown a Holocene period of halite deposition dated at 2.5 ± 1.2 ka.

INTRODUCTION

Webbs Cave is located in the Mundrabilla area, a central portion of the Nullarbor Plain (Figure 1). The name "Nullarbor" is applied to an extensive area of semi-arid karst underlain by marine limestones ranging in age from Eocene to Miocene. Most of the Plain consists of an extensive plateau, the Hampton Tableland, reaching a maximum surface elevation of 240 m in the north-west and declining towards the coast where for much of its length it terminates in spectacular coastal cliffs up to 90 m high.

In the central portion of the plain, including the region south of the Mundrabilla area, the Hampton Tableland is separated from the coast by a low-lying limestone erosional surface, the Roe Plains, covered by a thin veneer of early Pleistocene marine sediments. The Roe Plains are separated from the Hampton Tableland by the Hampton Range, a relict seacliff dissected by short ephemeral stream channels with associated alluvial fans.

The area has a semi-arid climate with a mean annual precipitation of approximately 250 mm characterised by a

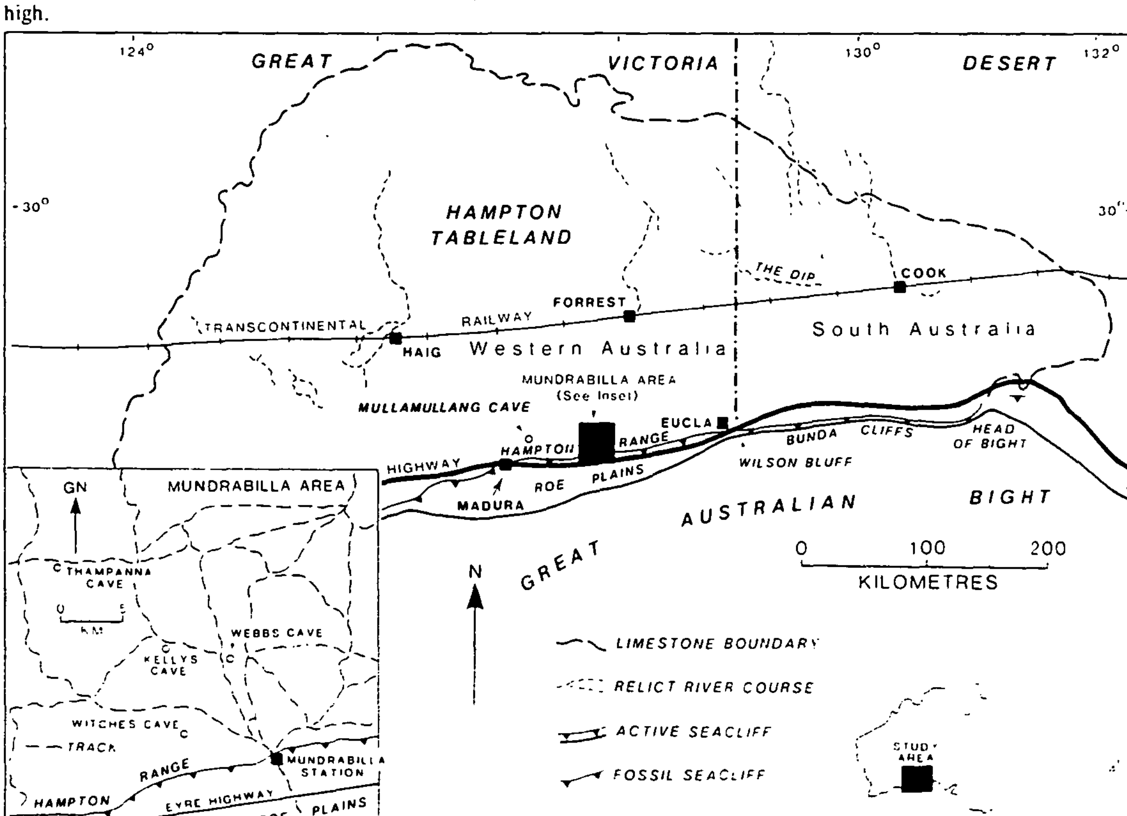

Figure 1. Location of the Nullarbor karst showing the Mundrabilla area and cave localities (after Goede et al., 1990).

winter maximum. The mean annual temperature is 19°C and cave temperatures are usually within 1°C of this figure (James, 1991).

The Roe Plains in the Mundrabilla area are approximately 30 km wide. Webbs Cave is located on the Hampton Tableland some 9 km north of the Hampton Range. A number of other caves are known in the area and have been discussed in more detail elsewhere (Goede *et al.*, 1990; James, 1991). Webbs Cave falls within the coastal belt of woody vegetation dominated by species of eucalypts and acacias. Further inland the vegetation grades into a treeless steppe dominated by halophytic plants.

The Mundrabilla caves are relatively rich in calcium carbonate speleothems but much of the material has been severely fragmented by subsequent salt wedging. Uranium series dating has shown that the major periods of carbonate deposition predate 400 ka (Goede *et al.*, 1990) but there are minor exceptions with modern carbonate deposition taking place in the entrance chambers of a few caves, e.g. Thampanna Cave (James, 1991; Eberhard, 1991) and Jimmy's Cave (Goede *et al.*, 1990). It occurs where such chambers are located beneath large dish-shaped depressions that concentrate surface drainage.

Gypsum and halite speleothems are abundant in some of the Mundrabilla Caves. Considerable amounts of halite have also been reported from some caves elsewhere in the plain, e.g. Salt Cellars in Mullamullang (Dunkley & Wigley, 1967). Halite speleothems are usually in the form of wall crusts, fissure fillings and extrusion forms - types that do not require rapid evaporation of seepage water.

Gypsum stalactites and stalagmites have been observed in Kelly Cave (Appleyard, 1980) and Thampanna Cave (Goede *et al.* 1990; James, 1991) with currently active forms occurring in the latter.

Active halite stalactites were seen in Kelly Cave during a visit in 1981. Halite stalagmites have so far been observed only in Webbs Cave and their occurrence world-wide appears to be extremely rare. Jennings (1981) observed a 500 mm tall halite stalagmite from Central Asia on display in the Museum of Geology in Peking, China. No other references to halite stalagmites are known to the authors. The formation of halite stalactites and especially stalagmites would require extremely rapid evaporation of drip waters to ensure supersaturation. Low humidity of the cave atmosphere alone may not be able to achieve this and may have to be combined with strong air currents. Strong air movement is well known in Webbs Cave, where it has also contributed to the high level of salt wedging of both carbonate speleothems and limestone bedrock (see photograph 5 in Jennings, 1983).

The halite stalagmite discussed here was discovered in Webbs Cave in April, 1981 by one of the authors (A.G.) and A. Davey. It was reconstructed from 10 major and several minor fragments (Figure 2) found scattered around the floor of the chamber. The fragments were fitted together to form a stalagmite 2780 mm tall prior to its collapse. Collapse appeared to have been due to attack by aggressive drip water subsequent to its deposition. The water dissolved a half tube down the side of the stalagmite which passed through it at the base as a cylindrical solution tube.

The party was not equipped to collect the specimen and maintain it in a suitable condition for later analysis. However, one of us (A.G.) collected a 160 mm high halite stalagmite from Webbs Cave for experimental uranium series dating. Multiple dates were successfully obtained and the results reported (Goede *et al.*, 1990). It was found to have been deposited quite rapidly at about 4 ka BP. On the instigation of the late Dr Joe Jennings who had christened the specimen "Big Salty", a special trip was made from Canberra by Adrian Davey and Andy Spate to collect the broken stalagmite fragments in August 1981.

At the Australian National University six samples of 150 gm each were cut at intervals from the core of the speleothem for the purpose of uranium series dating. The samples were sent to Dr Russell Harmon at the Scottish Research and Reactor Institute at East Kilbride, Scotland. One surface and one interior sample were also collected for chemical analysis and the results have been reported by Caldwell *et al.* (1982). The re-

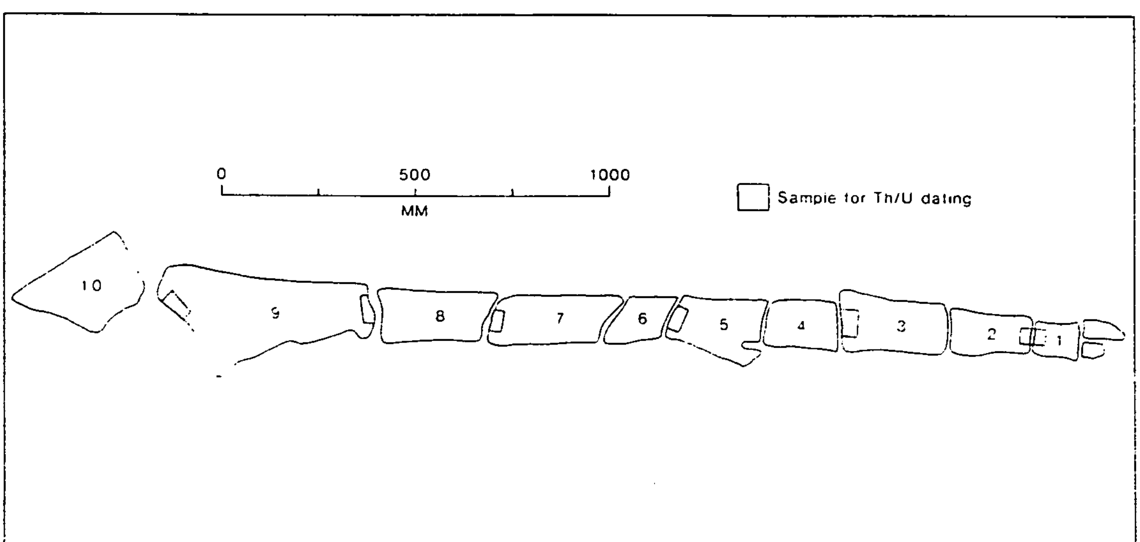

Figure 2. Sketch of "Big Salty" made at the Australian National University when it was sampled for Th/U dating

mainder of the specimen was sent to the West Australian Museum where it was added to their collections and will eventually be placed on display.

When the samples for uranium series dating reached Scotland, Dr Russell Harmon was about to depart for the Southern Methodist University at Dallas, Texas, to take up a new appointment. He took the samples with him as he intended to set up a new laboratory. Unfortunately, because of lack of financial support, the new dating laboratory never became a reality. After some years the samples were sent to the University of East Anglia for Th/U analysis by two of us (T.C.A. & P.J.R.) and the results are reported in this paper.

CHEMICAL COMPOSITION & PHYSICAL NATURE

As already mentioned, two samples were examined by Caldwell *et al.* (1982) and the results reported. An interior sample (19) was pure white in colour and chemical analysis revealed a halite content of 95.8%. The main impurities expressed as percentages were Ca (.29), Mg (.12), K (.72), SO_4 (.06), HCO_3 (.15), Br (.20) and H_2O (2.04). The total percentage analysed was 99.4% and pigmented residues were reported to be absent.

A sample of surface skin (20) was examined and found to contain more substantial amounts of gypsum and calcite in the form of sand and silt-sized crystals than the interior of the stalagmite. The sample colour was very pale brown to light yellow brown and this was found to be due to the presence of some organic carbon and a small amount of iron (Fe 0.4%). The distinctive nature of the surface skin was interpreted as being due to re-solution and re-deposition effects. In support of this the authors reported the presence of "a half-round re-solution channel running down the side of the stalagmite, which near the base goes inside it, emerging as a cylindrical hole at the base" (Caldwell *et al.*, 1982).

RADIOMETRIC DATING

The $^{230}Th/^{234}U$ method of uranium-series disequilibrium dating has long been applied as a reliable technique to date carbonate speleothems (Gascoyne & Schwarcz, 1982). It has also been successfully applied to evaporites found in lake sediments including halites (Peng *et al.*, 1978). Since no Th/U dating of halite speleothems had been reported, experimental dating was first attempted on a 160 mm high stalagmite also collected from Webbs Cave. This was found to contain uranium concentrations of 0.1 mg kg $^{-1}$. With only minor detrital contamination this was adequate to obtain meaningful dates. The procedure followed was similar to that used to date carbonates and details have been reported by Goede *et al.* (1990). The authors presented details of the analyses and the dates obtained.

Analyses of both the top and basal samples of the large stalagmite were initially attempted using 60 gm weight for each but this proved to be unsuccessful as the uranium concentration in both cases was found to be too low to measure. This was very unfortunate as it made it impossible to determine the $^{230}Th/^{234}U$ ratios of the individual samples to obtain a series of dates that would have provided reliable estimates of the growth rates and the time span over which the halite had been accumulating. In an attempt to obtain an approximate age for the period of halite formation all the remaining sample material was bulked and analysed as a single sample. The results of the analysis are shown in Table 1.

Table 1

Sample weight 776.8 g	Detrital weight (acid insoluble) = 0.05 g
U conc. 0.0023 ppm	
Chemical Yields: U 21.2% Th 77.2%	
$^{234}U/^{238}U = 0.636 \pm 0.023$	$^{230}Th/^{232}Th = 3.918 \pm 0.341$
$^{230}Th/^{234}U = 0.297 \pm 0.014$	
Uncorrected date = 39,700 ± 2300 years	

The very low $^{230}Th/^{232}Th$ ratio indicates detrital contamination despite the low detrital content of the bulk sample and reflects a problem associated with the very low concentration of radio-isotopes. The ratio indicates that the sample is probably younger than the uncorrected date of 39.7 ka. Correcting for detrital Th only (not U) using the method of Schwarcz (1980, p. 20 eqn. 8) yields the following range of corrected dates (Table 2) using initial $^{230}Th/^{232}Th$ ratios in the range of 0.25 to 2.00.

It is difficult to assess which of these ratios is the most appropriate in this case. We have chosen values that span the range deduced by other workers, either by comparison with independent dating techniques (Kaufman and Broecker, 1965; Kaufman et al. 1971) or from a *"common-age"* determination following multiple sample analysis (Ku et al., 1979).

Table 2

Initial ratio $^{230}Th/^{232}Th$	0.25	0.50	0.75	1.0	1.25	1.50	1.75	2.0
Corrected date (ka)	37.5	35.2	32.9	30.6	28.2	25.8	23.3	20.8

It can be concluded that the material has an apparent age in the range 21-38 ka. Since the date is based on a bulk sample of all the material that remained after the initial pair of analyses it must be considered as meaningful only in that it indicates a late Last Glacial age for the stalagmite.

DISCUSSION

On a world scale halite speleothems in caves of semi-arid and arid regions appear to be uncommon (White, 1976) and the occurrence of halite stalagmites extremely rare. To our knowledge only one other occurrence, from Central Asia, has been reported in the literature (Jennings, 1981). It has also been asserted by Jennings (1983) that the "Nullarbor caves are particularly rich in halite, ...".

The occurrence in caves of chemical deposits that are predominantly composed of carbonate, sulphate or halide deposits can be seen as a logical sequence when progressing from humid to arid environments with no chemical deposition at all under conditions of extreme aridity.

Halite may be derived from different sources. Sodium chloride may have been stored within the limestone since the time of its deposition. However, since the limestones that underlie the Nullarbor Plain have been above sea level for at least ten million years and since for a large part of this time they have probably been subjected to significantly wetter conditions than prevail today, it seems improbable that primary salt is a significant source. Halite may also be released as a result of the weathering of primary minerals but the possible content of such minerals will be very low in a pure limestone.

It is highly probable that the bulk of the sodium chloride is of oceanic origin and has been carried inland from the Great Australian Bight by SW and S winds. Such an origin is strongly favoured by the evidence from groundwater composition. Total salinity, dominated by chloride, ranges from an average of 2,500 ppm in the northern part of the plain to 35,000 ppm beneath the Roe Plains (Lowry & Jennings, 1974). This trend occurs despite a significant increase in precipitation towards the coast and strongly supports a cyclic origin for the chloride.

As long as there is sufficient precipitation to provide downward percolation in the vadose zone, significant accumulation of halides in the soil is unlikely as the primary permeability of the limestone is high. The plateau however is covered by a variety of calcareous soils including significant amounts of concretionary calcium carbonate - sufficiently massive in places to form a calcrete. Such soils can cause temporary surface and sub-surface ponding of water causing large evaporation losses especially in summer. Under sufficiently dry conditions this may lead to little or no downward percolation and a build-up of halites in the soil. A change to slightly wetter and/or cooler conditions may cause resumption of percolation, but with a very high content of soluble salts. Such a situation could lead to the deposition of halite speleothems provided that the seepage water is subject to strong evaporation on coming into contact with the cave atmosphere.

Richards (1971) has reported relative humidities ranging from 83% to 100% in the Nullarbor caves and this may be sufficient to cause the formation of halite wall crusts and extrusion speleothems common in some of the caves. The formation of stalactites and stalagmites takes place under conditions of more rapid water movement and strong air movements may be required to cause their accumulation.

Strong air currents have been observed not only in Webbs Cave where halite speleothems are found but also in nearby Kelly and Thampanna Caves where similar forms are composed of gypsum.

If the formation of halite stalactites and stalagmites is due to the flushing out of cyclic salts that have accumulated in the calcrete capping, halite deposition can be expected to cease and may give way to resolution processes when the soil store of cyclic salts is depleted. Re-solution may continue until percolation ceases with a return to drier conditions.

Goede *et al* (1990) when discussing the dating of a small halite stalagmite from Webbs Cave, pointed out that the $^{234}U/^{238}U$ ratios of 0.73 to 0.78 found in this speleothem, were much less than the value of 1.14 normally found in seawater. The ratio for the big halite stalagmite at 0.64 is even lower (Table 1). They suggested that "the source of uranium in the stalagmite is not directly from sea spray or derived from marine salts in rainfall". Such a low activity ratio indicates "that the percolating water dissolved uranium from a second source which had already been subject to extensive leaching. The second source is believed to be either the limestone above the cave and/or the calcrete capping, both exposed to extensive leaching over a long period of time. It supports the suggestion that the soluble salts, while ultimately of marine origin, were stored in the overlying soil or bedrock for a significant time period. The $^{234}U/^{238}U$ ratio of the big stalagmite may be lower than that of the small stalagmite due to a reduced marine influence at a time when sea levels were low and the coast considerably more distant.

CONCLUSIONS

The dating of "Big Salty", while imprecise, is the first evidence of Late Pleistocene halite deposition from a Nullarbor cave. Taken together with the earlier dating of the small halite stalagmite (W-1) from Webbs Cave at 2.5 ± 1.2 ka it indicates clearly that there have been at least two phases of formation of halite stalagmites.

These phases are interpreted as slight swings to a more humid environment following periods of cessation of percolation under conditions of aridity, sufficiently extreme to have caused accumulation of soluble salts in the soil/calcrete zone. Deposition is believed to be associated with downward flushing of salts from the soil zone and would have continued until the bulk of the accumulation had been flushed out. At this stage the percolation ceased to become saturated and resolution occurred until percolation ceased with a return to more arid conditions.

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A DIVERSE HOLOCENE MOLLUSCAN FAUNA, INCLUDING *ANADARA TRAPEZIA*, FROM ROYAL PARK, LAUNCESTON, TASMANIA

by A. Goede, C.V. Murray-Wallace and E. Turner

(with three tables and two text-figures)

GOEDE, A., MURRAY-WALLACE, C.V. & TURNER, E., 1993 (31:viii): A diverse Holocene molluscan fauna, including *Anadara trapezia*, from Royal Park, Launceston, Tasmania. *Pap. Proc. R. Soc. Tasm.* 127: 17–22. ISSN 0080–4703. Department of Geography and Environmental Studies, University of Tasmania, GPO Box252C, Hobart, Tasmania 7001 (AG); Department of Geology, University of Wollongong, Wollongong, NSW 2522 (CM-W); and Tasmanian Museum and Art Gallery, GPO Box 1164M, Hobart, Tasmania 7001 (ET).

Estuarine sediments exposed during road construction at Royal Park in the City of Launceston, northern Tasmania, were found to contain a diverse molluscan fauna with some 40 species identified. An unusual occurrence was the presence of six specimens of *Anadara trapezia*, a species not previously encountered *in situ* in Quaternary marine or estuarine deposits in Tasmania. Amino acid racemisation and electron spin resonance, calibrated against radiocarbon dating, point to a late Holocene age for this estuarine sequence. A numeric age of 2600 ± 400 yrs BP was derived for a specimen of *A. trapezia*, based on the extent of leucine and valine racemisation. Electron spin resonance data are consistent with this age assessment. The presence of *A. trapezia* in late Holocene sediments at Launceston may imply slightly warmer water temperatures during the late Holocene.

Key Words: Holocene, estuarine molluscs, amino acid racemisation, electron spin resonance, Tasmania.

INTRODUCTION

The shell bed was discovered during excavations for the Wellington Street overpass and drawn to the attention of the Queen Victoria Museum and Art Gallery by the site engineer (fig. 1). The material was collected by Mr Ron Kershaw and Dr Bob Green, in or about 1980, and lodged with the Museum collections.

A note with the collection stated that the material was recovered c. 3.6 m below the surface during excavations for the extension overpass. There is no stratigraphic description, but a significant amount of shelly sand matrix was collected. No record was kept of the overlying sediments, and it is not known to what extent they represent estuarine infilling or urban landfill.

The discovery was recorded by Van de Geer (1981), who tentatively suggested a Pleistocene age. He pointed out that *Anadara trapezia* has never been recorded from Holocene marine deposits in Tasmania, but is widely reported from coastal deposits of Last Interglacial age in the southern mainland states of Australia (Ludbrook 1984), in contrast with a more restricted geographic coverage during the Holocene. The considerable overburden reported from the site, if natural, also appeared consistent with a late Pleistocene age, based on geomorphological reasoning and known rates of estuarine sedimentation.

R.C. Kershaw (pers. comm., 1988) indicated that the site was at the outer edge of the existing floodplain of the Tamar River, and that the bank sloped steeply upwards from this position (fig. 2). The site was reported to be 40 m northwest from the northwest corner of the Supreme Court building and 225 m due east of the Tamar Estuary (grid ref. 511050mE, 5412565mN). The surface of the site was less than 1 m above high tide level and is known to have been subject to flooding during historical times.

A full description of the species content is given, together with an account of the palaeoecological conditions. Two Quaternary dating techniques calibrated against the radiocarbon method were also applied to specimens of *Anadara trapezia* and *Katelysia rhytiphora* from this deposit. These dating methods have previously been applied to several other Tasmanian Quaternary coastal fossil shell localities (Murray-Wallace & Goede 1991).

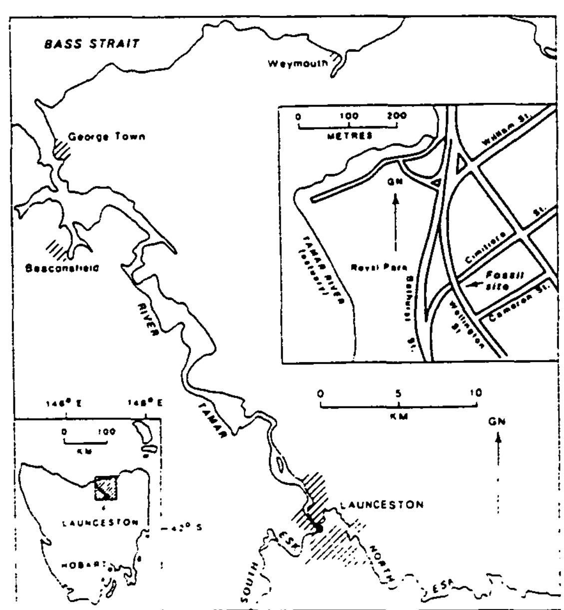

FIG. 1 — Locality map of Launceston area with inset map showing position of fossil site.

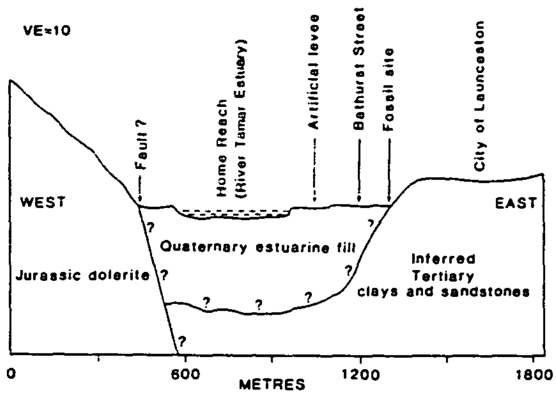

FIG. 2 — Cross-sectional diagram showing relationships of site to topography and geological substrate.

SEDIMENT CHARACTERISTICS

The host sediment is represented by poorly sorted, pale orange-brown quartz sands of mixed fluvial and marine provenance. Grain size ranges from very fine to medium sand size, and the sediment comprises a heterogeneous mixture of coarser-grained, subrounded quartz grains, with frosted surfaces, and finer-grained, angular quartz, with either a vitreous lustre or milky surfaces. Approximately 3% of the sediment consists of coarse (c. 2 mm long axis) shell fragments of unrecognisable affinity and a few prismatic grains of mica. Some micro-gastropods are also present.

SPECIES COMPOSITION AND ECOLOGY

The diverse molluscan fauna recovered from the site is listed in table 1. Some species are represented only by a few fragments, the majority by one to six specimens, while only five species were abundant: *Bittium granarium, Diala lauta, Batillaria australis, Katelysia scalarina* and *K. rhytiphora.*

The fossil assemblage indicates that during deposition the site represented a marginal marine environment characterised by tidal sand and mudflats. A beach may have been present.

Virtually all species are consistent with Holocene and modern populations found in similar environments in Tasmania. An exception is *Anadara trapezia.* Living specimens have not been recorded from Tasmanian waters, although shells are occasionally found washed up on beaches (Sutherland & Kershaw 1971).

Ecological preferences of species are also shown in table 1. The majority are tidal sand or mudflat dwellers, which either browse or filter-feed on the sandy floor or burrow just below the surface of the sand. They are typical of species which prefer quiet, sandy, sheltered bays, inlets and estuaries. Such environments are usually dominated by bivalves, but several gastropods are also found browsing on seagrass or scavenging around tidal sand and mudflats. The presence of littorinid and trochid species indicates that the immediate area was partially rocky, with associated rockpools. Other species present may live on rocks, on algae, in crevices or under rocks. Mudflats are indicated by the presence of some species (*Batillaria australis, Nassarius* spp., *Anadara trapezia* and *Spisula trigonella*) and are the only indication of a freshwater influence.

TABLE 1
Species list of subfossil shells from Royal Park, Launceston, and their ecological preferences

Taxon	Ecological Preference
GASTROPODA	
Alaba monile (A. Adams, 1862)	algae, sea grass
Astralium (Micrastraea) aurea (Jonas, 1844)	on rocks
Batillaria lawleyanum (Crosse, 1863)	mud
B. australis (Quoy and Gaimard, 1834)	mud
Bembicium auratum (Quoy and Gaimard, 1834)	on rocks
B. melanostoma (Gmelin, 1791)	on rocks
Bittium granarium (Kiener, 1842)	sand, weed
Bulla quoyi (Gray, 1827) (syn. *Bullaria botanica)*	sand, mud, weed
Cominella eburnea (Reeve, 1846)	sand, rockpools
C. lineolata (Lamarck, 1809)	sand, rockpools
Conuber conicus (Lamarck, 1822)	sand, mud
Dentimitrella tayloriana (Reeve, 1859)	under rocks at low water
Dentimitrella sp. (fragment)	under rocks at low water
Diala lauta (A. Adams, 1862)	algae, sea grass
Gibbula (Cantharidella) tiberiana (Crosse, 1863)	algae, sea grass
Monodonta (Austrocochlea) constricta zebra (Menke, 1829)	sea grass
Nassarius burchardi (Philippi, 1851)	sand, mud
N. nigellus (Reeve, 1854)	sand, mud
N. pauperatus (Lamarck, 1822)	sand, mud
N. pyrrhus (Menke, 1843)	sand, mud
Phasionella sp.	algae
Pleuroploca australasia (Perry, 1811)	sand
Salinator sp.	sand, mud
Seila sp. (probably *S. insignis* (May, 1911))	deep water
Zeacumantus diemenensis (Quoy and Gaimard, 1934)	sand, mud, weed
BIVALVIA	
Anadara trapezia (Deshayes, 1840)	mud
Eumarcia fumigata (Sowerby, 1853)	sand, sandy mud
Fulvia tenuicostata (Lamarck, 1819)	sand, mud
Irus crenatus (Lamarck, 1818)	on rocks, in cavities
Katelysia rhytiphora Lamy, 1937	sand, mud
K. scalarina (Lamarck, 1818)	sand, sandy mud
Notolepton sp.	algae, sea grass
Ostrea angasi Sowerby, 1871	on rocks, sand, mud
Sanguinolaria biradiata (Wood, 1815)	sand
Spisula trigonella (Lamarck, 1818)	sand, sandy mud
Tawera sp. (fragments)	sand
Tellina deltoidalis Lamarck, 1818	sandy mud
T. mariae Tenison Woods, 1876	sand
Venerupis anomala (Lamarck, 1818) (syn. *Pullastra fabagella)*	gravelly sand
Wallucina assimilis (Angas, 1867)	sand

Four species are essentially estuarine on the basis of the definitions used by Wells (1984). In addition, *Bembicium melanostoma* should also be regarded as such in a Tasmanian context (R.C. Kershaw, pers. comm.). The remaining 34 species are adapted to the marine aspect of the estuarine biota. Many were recorded by Kershaw (1958) as intertidal species at Kelso and Greens Beach, close to the estuary mouth. The present distribution of this fauna indicates a downstream shift of some 40 km in the marine-dominated estuarine environment, subsequent to the accumulation of the Royal Park sediments.

European settlement is certain to have changed the area beyond all recognition, due to land reclamation and filling, dredging, accelerated erosion in the catchments of the South Esk and North Esk Rivers, agricultural drainage, stormwater run-off and the introduction of new species of plants and animals.

METHODS

Amino acid racemisation (AAR)

This method involves analysis of the amino acid content of the shells. Amino acids persist for lengthy periods after death but undergo structural and chemical changes, which are predominantly a function of the diagenetic temperature history and other time-dependent parameters.

In the protein of all living organisms, amino acids occur almost exclusively in the L (laevo rotatory or left-handed) configuration. This is due to a variety of enzymic reactions, which prevent the development of D-amino acids during life. However, following the death of an organism, these enzymic reactions cease, and amino acids undergo a slow change to the D (dextro rotatory or right-handed) configuration until equilibrium (i.e. 50:50 mixture of L- and D-amino acids). This change is known as racemisation. Dating requires measurement of the D/L ratio, which is determined by gas chromatography. The higher the D/L ratio, the greater the age of a fossil. Advantages of the method include the wide timespan it serves and the fact that small samples (<1 g) may be analysed. Analytical techniques and sampling strategies are described by Kimber & Griffin (1987) and by Murray-Wallace & Kimber (1987). Analyses are reported for several enantiomeric amino acids that include valine (VAL), leucine (LEU), proline (PRO), aspartic acid (ASP), phenylalanine (PHE) and glutamic acid (GLU). Isoleucine results are not reported here because of poor baseline resolution during chromatography.

Electron Spin Resonance (ESR)

This method is based on the fact that many natural materials, of either mineral or biological origin, tend to accumulate radiation defects over time. Dating requires the measurement of concentrations of ionised particles that build up in different kinds of traps within the crystalline lattice of the material. The radiation dose has two components. An internal dose is generated by the presence of radioactive isotopes within the sample (mainly U, Th and K). The external dose is due predominantly to radioactive impurities in the immediate environment of the sample, predominantly within 300 mm radius, with a small contribution from cosmic radiation.

The absorbed radiation dose or gamma equivalent dose (ED) is measured in gray (Gy) and can be determined using an ESR spectrometer. Details of the technique and of the sample preparation procedures can be found in Goede & Hitchman (1987) and Goede (1989). Approximately 10 g of material is required for analysis.

If both the internal and external annual dose rate are determined, it is possible to obtain a numerical age since

$$\text{Age} = \text{ED/annual dose rate}$$

In practice, numerical estimates involve several assumptions which cannot be verified, and it has been argued that the method is better suited as a relative dating method (Goede 1988); this approach is followed here.

DATING

Amino Acid Racemisation

Parts of the hinge region of a single shell of *Anadara trapezia* were used to assess the extent of AAR. Analytical results are shown in table 2 and compared with analyses from two other Tasmanian Holocene shell sites. The latter have also been dated, using radiocarbon methods (Murray-Wallace & Goede 1991). The Royal Park amino acid data are also compared with modern and Last Interglacial (c. 125 000 yrs BP) specimens of *A. trapezia* from southern mainland states of Australia.

Comparison of these results indicates clearly that the *Anadara* sample from Royal Park is of late Holocene age (i.e. <6000 yrs BP by analogy with the radiocarbon dated samples [table 2]). Most of the amino acids in the sample show significantly lower D/L ratios than samples from the other two Holocene sites and therefore imply a Holocene age for the specimen of *A. trapezia* (table 2).

Similarly, the extent of racemisation of amino acids in the Last Interglacial specimens of *A. trapezia* from South Australia and in the modern sample from Quarantine Bay in southern New South Wales, effectively bracket the Royal Park data, and show conclusively that the *Anadara* from Royal Park is not Last Interglacial in age.

A numerical age assessment for the *Anadara* specimen from Royal Park was undertaken, using the integrated rate expression for racemisation (Schroeder & Bada 1976). Radiocarbon-dated specimens of *Glycymeris (Tucetilla) striatularis* (6100 ± 180 cal BP: SUA-2833) from Shell Pitts Point in northwestern Tasmania (Murray-Wallace and Goede 1991) were used as a framework to calibrate the amino acid data for the Royal Park *Anadara*. An empirically derived racemisation rate constant (k) of 1.16×10^{-5} was determined on this basis and a numerical age of 2600 ± 400 yrs BP is indicated for the *Anadara* specimen from Royal Park. The numerical age assessment is based on the extent of leucine and valine racemisation.

Electron Spin Resonance

Attempts were made to analyse two shell samples, one consisting of two valves of *Anadara trapezia* and another of three valves of *Katelysia rhytiphora*. It proved to be impossible to obtain an ED value for *Anadara*, as analysis did not yield a characteristic ESR aragonite spectrum. Remains of a third *Anadara* shell, partly used for AAR analysis, were examined by X-ray diffraction, and the material was found to be aragonite. The unusual spectrum of the *Anadara* ESR sample remains unexplained.

Excellent results were obtained for *Katelysia rhytiphora*. An ED value of 5.3 Gy was determined with 95% confidence limits of 1.9 and 8.8. In table 3 this value is compared with ED values obtained for nine samples drawn from four other Tasmanian sites. The ED value is significantly lower than those for three of the other Tasmanian sites, including the Shell Pits Point and The Spit sites, both radiocarbon dated with calculated ages of c. 6500 yrs BP. The Royal

TABLE 2
Extent of amino acid racemisation ("total acid hydrolysate") in Holocene mollusca from Tasmania, compared with modern and late Pleistocene specimens of *Anadara trapezia* from the southern mainland states of Australia

Locality	Species	Lab code	Conventional age (BP)	Calibrated age (cal BP)*	Amino acid D/L ratio					
					VAL	LEU	PRO	ASP	PHE	GLU
Quarantine Bay, southern NSW	*Anadara trapezia*	–	(modern)	–	0.02	0.03	–	0.11	–	0.08
Royal Park, Launceston	*Anadara trapezia*	–	–	–	0.04 ± 0.003	0.07 ± 0.03	0.05± 0.005	0.17 ± 0.001	0.11 ± 0.002	0.05 ± 0.002
"The Spit", Ralphs Bay	*Katelysia scalarina*	SUA-2294R	6150 ± 60	6580 ± 160	0.05 ± 0.002	0.14 ± 0.02	0.18 ± 0.01	0.28 ± 0.001	0.11 ± 0.001	0.09 ± 0.006
"The Spit", Ralphs Bay	*Fulvia tenuicostata*	SUA-2294R	6150 ± 60	6580 ± 160	0.11 ± 0.01	0.16 ± 0.01	0.11 ± 0.01	0.19 ± 0.01	0.12 ± 0.02	0.11 ± 0.01
Shell Pits Point, NW Tasmania	*Glycymeris (Tucetilla) striatularis*	SUA-2833	5700 ± 70	6100 ± 180	0.09 ± 0.01	0.17 ± 0.01	–	0.33 ± 0.01(?)	0.16 ± 0.05	0.15 ± 0.01
Woakwine Range, (lagoon facies) Robe SA	*Anadara trapezia*		(late Pleistocene: c. 125 000 yrs BP)		0.20 ± 0.01	0.35 ± 0.01	–	0.47 ± 0.003	0.42 ± 0.01	0.32 ± 0.01

* Calibrated radiocarbon ages (cal BP) include a correction for the marine reservoir effect for southern Australian coastal waters. This involved the subtraction of 450 ± 35 years from the conventional radiocarbon age (Libby half-life of 5568 years) according to the principles outlined by Gillespie & Polach (1979). Radiocarbon calibration is after Stuiver *et al.* (1986).

TABLE 3
Summary of ESR analytical data on Holocene molluscan shells from Tasmanian deposits

Sample No.	Species	ED (Gy)	95% conf. limits
Royal Park, Launceston			
T20	*Katelysia rhytiphora*	5.3	1.9–8.8
Shells Pits Point, NW Tasmania			
T10	*Fulvia tenuicostata*	26	21–30
T16	*Katelysia rhytiphora*	18	14–21
Perkins Island, NW Tasmania			
T7	*Fulvia tenuicostata*	20	16–24
T12	*Glycymeris (T) striatularis*	15	10–20
The Spit, Ralphs Bay			
T15	*Katelysia scalarina*	13	10–16
F74 (1)	*Fulvia tenuicostata*	19	16–22
F79 (1)	*Katelysia scalarina*	13	12–15
Shelly Beach, Ralphs Bay			
F68 (1)	*Fulvia tenuicostata*	6.4	4.6–8.2
F68 (2)	*Fulvia tenuicostata*	10	8–13

Park ED value is comparable to two ED values obtained at Shelly Beach, South Arm Peninsula, for *Fulvia tenuicostata.* This site has a radiocarbon age of 2930 ± 80 cal BP (SUA-2293). Thus, the Royal Park sample appears to be of similar age. This is in good agreement with the age estimated by AAR. A z-score test indicates that the AAR derived age is not significantly different to this radiocarbon age ($z = 0.809$).

DISCUSSION

In Australia, including Tasmania, sea levels appear to have reached their present height c. 6500 ± 250 yrs BP (^{14}C) (Thom & Roy 1985). However, arguments continue concerning the extent of sea-level fluctuations since that time (Hopley 1983, Nakada & Lambeck 1989). Infilling of the Tamar Estuary must have proceeded continuously since that time. It is interesting to note that nearly 4000 years later the marine influence at Royal Park, near the head of the estuary, remained strong, suggesting that estuarine infilling that occurred up to this time had little impact on the ecology. This is believed to reflect low rates of natural denudation in the catchments of the South Esk and North Esk Rivers. The situation may well have continued until historical times.

Today, many of the shell species collected at Royal Park appear to be absent from this section of the modern estuary. Rapid siltation has become a major environmental problem (Foster *et al.* 1986). It has been estimated by Skirving (1989) that, under present-day conditions, the average annual input of suspended sediment into the Tamar Estuary is 56 900 tonnes/year. The bulk of this can be attributed to accelerated erosion due to forestry, mining, farming and road construction activities.

Estuarine silting has been further accelerated by the introduction of the saltmarsh grass *Spartina anglica* into the Tamar Estuary in 1947. It has very successfully colonised the upper third of the intertidal slope in most of the area. Before 1947, this area had been almost completely bare of vegetation. The saltmarsh grass has proved extremely efficient at promoting and stabilising deposition of silt (Phillips 1975, Pringle 1982).

An unusual feature of the site is the occurrence of the bivalve *Anadara trapezia.* This species has not been recorded *in situ* from any Quaternary marine, estuarine or beach deposits in mainland Tasmania or in the Bass Strait Islands (Colhoun *et al.* 1982, Jennings 1959, Sutherland & Kershaw 1971) nor has it been recorded live from Tasmanian coastal waters in historical times, but occasionally shells are washed up on Tasmanian beaches. Sutherland & Kershaw (1971) have recorded the presence of shells at Yellow Beach, south-east Flinders Island.

According to Gill (1977), its present southern limit in the southeastern mainland states is at Port Philip Bay, Central Victoria, where it occurs in small numbers and in smaller size compared with the mid-Holocene population. Gill also claimed that it has occurred in northern Tasmania in warmer times but provided no evidence.

Anadara trapezia first migrated into southern Australia some time during the middle Pleistocene, as penultimate interglacial (oxygen isotope stage 7: c. 220 000 yrs BP) occurrences have been dated from Peppermint Grove in the Swan Estuary, Western Australia (Hewgill *et al.* 1983, Murray-Wallace & Kimber 1989) and from Redcliff in northern Spencer Gulf, South Australia (Murray-Wallace *et al.* 1988). A possible older occurrence of the species has been cited by Gill (1977) in the Hopkins River Estuary at Warrnambool. However, relative ESR dating by Goede (1989) has shown that the site contains shell material of more than one age. The *Anadara trapezia* shell analysed from the site was found to be of Last Interglacial age.

If, as inferred by Gill (1977), the southern limit of the distribution of *Anadara trapezia* is controlled by water temperatures, conditions in the Tamar Estuary are likely to have been somewhat warmer than at present at the time of deposition of the Royal Park sediments. Therefore, the absence of *A. trapezia* in the Tamar Estuary may be related to a late Holocene cooling event. The exact sea level at that time is unknown. It was clearly no higher than today and may well have been lower.

CONCLUSION

Amino acid racemisation and ESR dating calibrated against radiocarbon indicate that estuarine sediments at Royal Park are of late Holocene age and are host to the estuarine bivalve *Anadara trapezia*. The variety and composition of molluscan species indicates a strong marine influence in the upper Tamar Estuary 4000 years after it was flooded by the Post-glacial marine transgression. This is also consistent with the nature of the host sediments.

The extremely high siltation rates observed at the present time are believed to reflect the combined effects of accelerated erosion of the catchment and the introduction of the saltmarsh grass *Spartina anglica*. The presence of *Anadara trapezia* is the first Tasmanian record of this species in a stratigraphic context and may well reflect slightly higher water temperatures than prevail today.

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CONTINUOUS EARLY LAST GLACIAL PALAEOENVIRONMENTAL RECORD FROM A TASMANIAN SPELEOTHEM BASED ON STABLE ISOTOPE AND MINOR ELEMENT VARIATIONS

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Abstract — A columnar stalagmite from a limestone cave in the Florentine Valley, Tasmania, has been dated by three $^{230}Th/^{234}U$ age determinations. Continuous profiles of 170 $\delta^{18}O$ and $\delta^{13}C$ values as well as magnesium and strontium concentrations are presented.

$\delta^{18}O$ values indicate temperatures lower than today with a gradual temperature decline in the basal part of the profile punctuated by two short cooling events and culminating in a double temperature minimum between 70 and 60 ka. The profile shows marked similarities with the GISP ice core record from Greenland which shows two short intense stadials centred on 74 and 70 ka preceding the Last Glacial temperature minimum. They have been correlated with 'Heinrich' events in North Atlantic marine cores which in turn have been attributed to periodic massive discharges of icebergs into the North Atlantic. The Tasmanian speleothem record suggests that these events may also have affected climates in the southern hemisphere.

The $\delta^{13}C$ variations also appear to indicate periodic environmental change. Minor element variations were found to be significantly correlated with isotopic changes. Strontium concentrations show a bimodal distribution indicating control by a switching mechanism tentatively attributed to variations in calcitic dust supply to the ground surface above the site.

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INTRODUCTION

The primary aim of this study is to present a continuous stable isotope ($\delta^{18}O$, $\delta^{13}C$) and minor element (Mg, Sr) record of the basal 860 mm of a 907 mm tall stalagmite (FT) which records deposition without any apparent hiati. The oxygen isotope data provide a proxy palaeotemperature record that is compared with other palaeoclimatic curves. The second aim is to investigate the significance of minor element variations and to compare them with the stable isotope record.

The speleothem was obtained from Frankcombe Cave, a system developed in folded Ordovician limestones in the Florentine Valley, south central Tasmania (146°27'06"E, 42°31'54"S) at an elevation of 360 m a.s.l. It was collected from a small chamber some 4 m above the floor of an intermittent stream passage. The cave has a mean annual temperature of 8.3°C with a range of 0.4°C (Goede *et al.*, 1982). Speleothem deposition occurred under conditions of near constant temperature approximating the mean annual temperature at the ground surface. The area has a temperate humid environment with precipitation throughout the year. The mean annual precipitation is approximately 1500 mm. The natural vegetation consists of wet sclerophyll forest extensively modified by clearfelling and burning. Stable isotope records based on interval sampling at about 1000 year intervals have been presented in an earlier paper (Figs 2 and 4) (Goede *et al.*, 1990).

Speleothems or cave calcite are deposited by precipitation of calcium carbonate as vadose seepage waters saturated with respect to carbonate and bicarbonate enter a cave and lose carbon dioxide to the cave atmosphere. While there is a wide variety of speleothem types, palaeoclimate research has been concentrated on columnar or uniform diameter stalagmites with deposition taking place from water dripping from the roof of the cavern (Harmon *et al.*, 1975). In longitudinal section such stalagmites are seen to consist of a core where vertical accretion takes place on a sub-horizontal surface forming a sequence of convex upward layers and a narrow mantle formed by discontinuous deposition on a near-vertical outer surface. Many such speleothems in humid temperate regions appear to grow continuously for long periods of time (typically 1 to 100 ka). Major growth hiati can usually be detected by an abrupt change in colour or depositional pattern, or the presence of detritus-rich layers derived either from airfall deposition or bacterial activity (moonmilk) or clastic sedimentation from floodwaters.

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The use of $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios of speleothem calcite to obtain palaeoclimatic information has been pioneered by Hendy and Wilson (1968) in New Zealand and Duplessy *et al.* (1970) in France. Hendy and Wilson found that $\delta^{18}O$ measurement would only reflect palaeotemperature if deposition had occurred under conditions of oxygen isotope equilibrium.

The use of δD values of fluid inclusions in speleothems was pioneered by Schwarcz *et al.* (1976). Until recently, quite large samples were required making replication of results difficult. It was also found by Yonge (1982) and Goede *et al.* (1986) that fluid inclusion waters have a systematic bias in δD of approximately 20‰ SMOW towards lighter isotopic values compared with the seepage waters from which they are derived.

The possibility that variations in the concentration of certain minor elements in speleothems may be indicative of environmental change has only recently begun to be explored (Gascoyne, 1983, 1992; Goede and Vogel, 1991). In contrast minor elements have been the subject of considerable study by earth scientists involved in the study of marine and lacustrine carbonate sediments. There has been particular emphasis on the possibility of using such elements as indicators of depositional temperature. Authors such as Katz (1973) and Fuchtbauer and Hardy (1976) showed that the homogeneous distribution coefficient of magnesium bears a positive relationship to temperature over the range 5–90°C.

Chivas *et al.* (1986) studied the magnesium and strontium content of lacustrine calcitic ostracod shells and found that in the temperature range 10–25°C magnesium content was a function of both temperature and salinity while the strontium content showed little if any temperature effect over the same range but was affected by changes in salinity.

Gascoyne (1983) was one of the first to investigate the possibility that minor elements might yield information about changes in the depositional environment of speleothems. He compared the distribution coefficients of magnesium between temperate (7°C) and tropical (23°C) cave sites and found significant differences. He concluded that magnesium content in speleothems varied directly with temperature in a sufficiently pronounced manner to detect temperature change as little as 1°C in the absence of other sources of variation. He then selected a speleothem from northern England that had been deposited under conditions of oxygen isotope equilibrium and took 21 samples along its growth axis that were analysed for both $\delta^{18}O$ values and magnesium content. No significant correlation between the two variables was found. Gascoyne (1992) tentatively attributed this to temporal variations in the Mg/Ca ratio in the seepage waters at the site.

Goede and Vogel (1991) examined the minor element composition of a stalagmite that had not been deposited under conditions of oxygen isotope equilibrium. It had been precisely dated by both uranium-series and radiocarbon dating and was shown to have been deposited between 15 and 11 ka — a known period of rapid climatic warming. Thirteen minor elements were found to be present in measurable amounts in fifteen samples. Using numerical taxonomy, the elements were classified into four groups on the basis of their behavioural similarity. One group, composed of four trace elements, showed a significant temporal trend which was upward for Mg, Sr and Ba and downward for Br. These four elements were regarded as showing the most promise as palaeoclimatic indicators.

Comparison of palaeoclimatic records requires the highest possible degree of precision and accuracy in dating. Radiocarbon can be used for the last 30 ka but while it provides high precision dates it tends to overestimate calendar ages by a variable amount depending on the nature of the limestone dissolution mechanism (Hendy, 1969; Wigley *et al.*, 1978; Gascoyne, 1992). However, approximate estimates of that amount can be made by combining radiocarbon dating with ESR analysis (Goede and Hitchman, 1984; Goede *et al.*, 1990).

Uranium-series disequilibrium dating using alpha spectrometry has the advantage that it can be used over a time interval of approximately 350 ka with reasonable precision and accuracy for samples with > 0.1 ppm uranium content and little or no detrital contamination (Gascoyne *et al.*, 1978). In recent years both the age range and precision of uranium-series dates have been greatly improved by the introduction of the mass spectrometric method (Li *et al.*, 1989; Ludwig *et al.*, 1992).

DATING

Full analytical details of the dating procedure are provided in Goede *et al.* (1990). Three uranium-series disequilibrium dates (Fig. 1) were used to determine the age scale used in Figs 2 to 7. The basal portion was not dated because of detrital contamination. The time-scale is based on the assumption of a uniform growth rate (Goede, 1991) by correlation regression analysis of height above base against the three age estimates suggesting that deposition occurred between 98 and 55 ka. However, because of the low uranium content of the speleothem the standard error for the basal date is particularly large.

Comparison with other proxy climatic records, discussed in more detail later, indicates clearly that the initiation of speleothem deposition postdates the beginning of marine isotope Stage 5a placed at 90 ka by Martinson *et al.* (1987). The original time-scale of Goede *et al.* (1990) is retained until such time as MS uranium-series analyses can provide more accurate dating.

THEORETICAL DISCUSSION

Hendy and Wilson (1968) have suggested the following two tests to establish the presence of oxygen isotope equilibrium:

(i) Absence of strong positive correlation between values of $\delta^{18}O$ and $\delta^{13}C$ when samples are taken from the

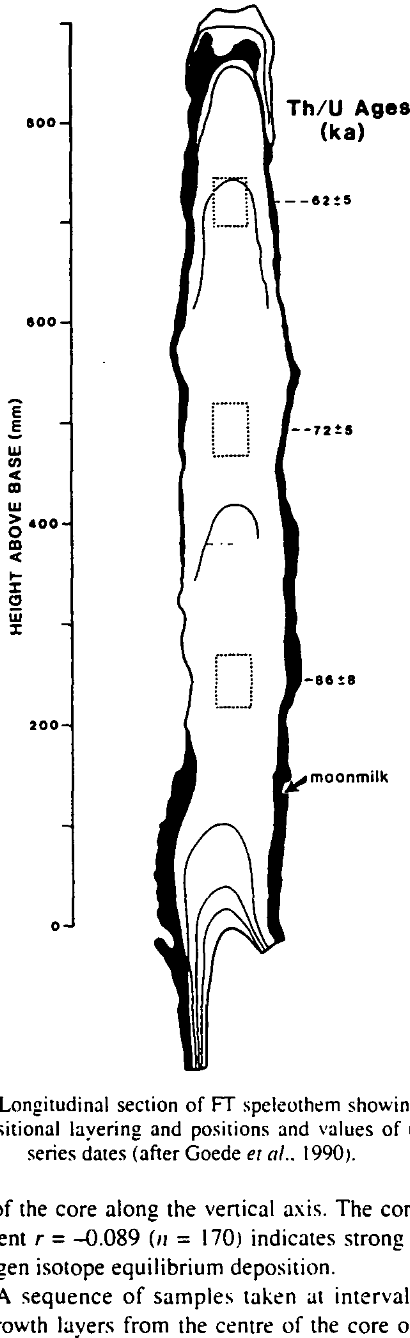

FIG. 1. Longitudinal section of FT speleothem showing nature of depositional layering and positions and values of uranium series dates (after Goede *et al.*, 1990).

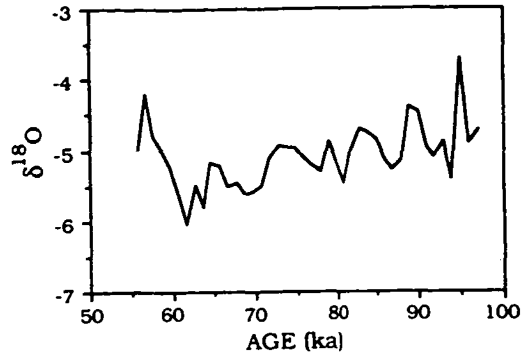

FIG. 2. Time series of oxygen isotope values based on interval sampling at 20 mm intervals using a 5 mm drill (after Goede *et al.*, 1990).

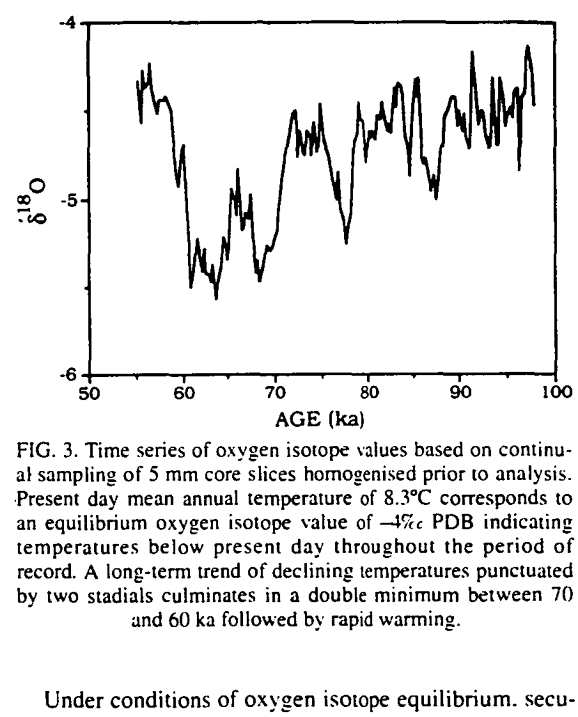

FIG. 3. Time series of oxygen isotope values based on continual sampling of 5 mm core slices homogenised prior to analysis. Present day mean annual temperature of 8.3°C corresponds to an equilibrium oxygen isotope value of –4‰ PDB indicating temperatures below present day throughout the period of record. A long-term trend of declining temperatures punctuated by two stadials culminates in a double minimum between 70 and 60 ka followed by rapid warming.

centre of the core along the vertical axis. The correlation coefficient $r = -0.089$ ($n = 170$) indicates strong support for oxygen isotope equilibrium deposition.

(ii) A sequence of samples taken at intervals along three growth layers from the centre of the core outwards show no progressive trend towards isotopically heavier values of $\delta^{18}O$ correlating with a similar trend in $\delta^{13}C$ values. Talma and Vogel (1992) have recently suggested that growth layer sampling should be restricted to the central sub-horizontal portion.

A further test is provided by a comparison of $\delta^{18}O$ and $\delta^{13}C$ values between samples drilled from the centre of the core, as in the earlier study (Goede *et al.*, 1990), and the core slices used in this study. If there had been disequilibrium deposition it would have shown as a systematic displacement towards heavier isotopic values in the core slices relative to the drilled samples. Such is not the case (compare Figs 2 and 3, Figs 4 and 5).

Under conditions of oxygen isotope equilibrium, secular changes in $\delta^{18}O$ values along the growth axis of the stalagmite are controlled by three major factors (Harmon *et al.*, 1978):

(i) Change in the temperature of the depositional environment of the cave. The cave temperature usually approximates the mean annual surface temperature and will respond to any change in the latter as climatic conditions change over time. The fractionation effect for $\delta^{18}O$ is –0.24‰/°C at 10°C.

(ii) Change in the isotopic composition of seawater due to the accumulation of glacial ice on land that is depleted in $\delta^{18}O$. The value of $\delta^{18}O$ of precipitation is estimated to increase 0.1‰ for every 10 m drop in sea level (Shackleton and Opdyke, 1973).

(iii) Change in isotopic composition of precipitation caused by temperature and humidity changes at the sites

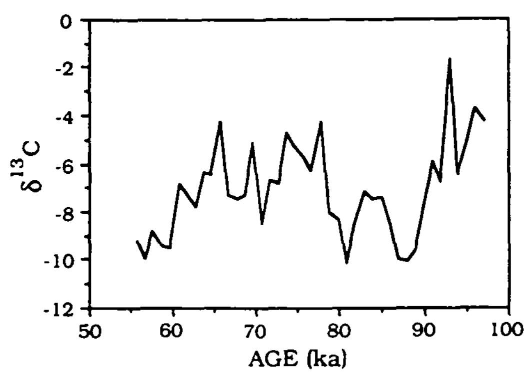

FIG. 4. Time series of carbon isotope values based on interval sampling at 20 mm intervals using a 5 mm drill (after Goede *et al.*, 1990).

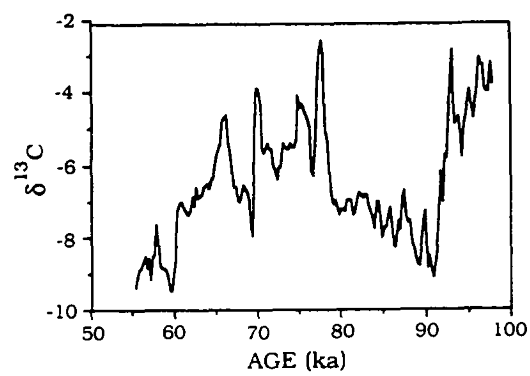

FIG. 5. Time series of carbon isotope values based on continuous sampling of 5 mm core slices homogenised prior to analysis. It contains two major peaks and two major troughs.

of evaporation and precipitation. Such changes may be further accentuated by a latitudinal change in the moisture source area as atmospheric circulation patterns respond to climatic change.

Changes in factors (i) and (ii) tend to cause ^{18}O isotopic enrichment during cold phases while factor (ii) has the opposite effect. In most areas so far examined factors (i) and (ii) predominate and a negative relationship occurs between $\delta^{18}O$ values of cave calcite and past temperatures. A positive relationship between the two has been shown for speleothems from Vancouver Island (Gascoyne *et al.*, 1980, 1981) and Tasmania (Goede *et al.*, 1986, 1990).

In Tasmania the modern $\delta^{18}O$ equilibrium value of cave calcite can be obtained either by calculation if the isotope composition of modern dripwater is known (Goede *et al.*, 1982) or by multiple sampling of straw stalactite tips where the isotopically lightest $\delta^{18}O$ associated with the isotopically lightest $\delta^{13}C$ value is taken as an approximation. At Frankcombe Cave the two methods yield modern $\delta^{18}O$ equilibrium values of −3.9 and −4.1‰ respectively so a value of 4.0‰ has been adopted (Goede *et al.*, 1990).

In Tasmania past values for equilibrium $\delta^{18}O$ in speleothems are nearly always isotopically lighter and may be as low as −6.2‰ for full glacial conditions. A positive relationship between $\delta^{18}O$ of cave calcite and temperature is also indicated by positive relationships between $\delta^{18}O$ of cave calcite and the δD values of fluid inclusions when both are sampled at the same stratigraphic level (Goede *et al.*, 1986, 1990). For further discussion see Gascoyne (1992).

METHODS AND INSTRUMENTATION

A half-core of speleothem FT was cut into 5 mm slices each representing approximately a 200–250 year period. Samples were then crushed and homogenised. Sub-samples were taken and CO_2 was prepared by reacting them in a vacuum with anhydrous H_3PO_4 followed by purification in a glass extraction line. $\delta^{18}O$ and $\delta^{13}C$ values were determined as ‰ PDB (Peedee Belemnite) using a VG SIRA Series II mass spectrometer with an average measurement precision of approximately 0.01‰. Because of suggestions that either variations in Mg content (Gascoyne, 1983) or the Mg/Sr ratio (Goede and Vogel, 1991; Goede, 1991) may at least in part reflect changes in temperature, the magnesium and strontium content were also determined for each sample. Analysis was done by atomic absorption spectrometry with a measurement precision of approximately 2%.

ANALYTICAL RESULTS

Data are presented of both the stable isotope and minor element analyses for 170 samples.

Stable Isotope Variations

The $\delta^{18}O$ values range from −4.14 to −5.57 ‰ PDB compared with a modern estimate of −4.0 ‰ (Fig. 3). As in Tasmania these values have been shown to have a positive relationship to temperature (Goede *et al.*, 1996, 1990), the average temperature for the entire period of record is inferred to have been below 8.3°C. There is a long term trend towards colder conditions until a double temperature minimum is reached between 70 and 60 ka — the early Last Glacial temperature minimum. There are no independent palaeotemperature estimates for this event in Tasmania but world-wide there is evidence that temperatures were almost as cold as the late Glacial maximum (Goede *et al.*, 1990). For the latter event Colhoun (1985) estimated a mean annual temperature lowering of 6.5°C for the West Coast Range in western Tasmania. The minimum isotope value of −5.57‰ at 60–65 ka may therefore correspond to a temperature lowering of some 6°C. On the assumption of a linear relationship between changes in palaeotemperature and $\delta^{18}O$ of cave calcite this gives a change of +0.26 ‰/°C.

The $\delta^{13}C$ values show a range of −2.57 to −9.56 ‰ PDB (Fig. 5). There is unusually wide variation for a speleothem deposited under conditions of isotope equilibrium. Since isotope fractionation does not appear to be responsible for the high values, another explanation has to be found. Goede *et al.* (1990) have speculated that at times deposition may have taken place in the absence of isotopically light (−27 to −13‰) biogenic carbon dioxide derived from a soil mantle. Dreybrodt (1982) has suggested that deposition of cave calcite could take place due to warming of vadose seepage waters during their passage through the bedrock but this has been shown to yield $\delta^{13}C$ values of between +6‰ and +10‰. Another explanation has been suggested by Gascoyne (1992) for Castleguard Cave in the Canadian Rockies. He argued that some CO_2 could be derived form oxidation of fossil organic matter in the overlying limestone. The Gordon Limestone in which the cave is developed is known to contain significant amounts of organic matter. The wide variation in $\delta^{13}C$ values may reflect temporal changes in the balance between biogenic carbon from the overlying soils and organic impurities from the limestone.

Minor Element Composition

Magnesium concentrations were found to range from 240 to 642 ppm and strontium concentrations from 45 to 158 ppm. The low magnesium concentrations are believed to reflect the nature of the bedrock. Much higher values (1813 to 3833 ppm) have been recorded for a northern Tasmanian speleothem (Goede and Vogel, 1991).

DISCUSSION

Isotopic variations in the $^{18}O/^{16}O$ content of speleothems are usually interpreted to reflect changes in mean annual temperature. However, in areas like Tasmania and Vancouver Island where oxygen isotope changes are dominated by changes in the isotopic composition of precipitation, the seasonal contribution of precipitation to seepage water is important. Gascoyne (1992, p. 617) has claimed that in cool climates, cave calcites are most likely to grow in the warmest months. This may be true in higher latitudes of the northern hemisphere where winter percolation may be prevented by seasonal freezing of soils. Under these conditions biogenic activity in the soils would also cease.

It has been shown that in the present day Tasmanian situation the isotopic composition of calcite is best related to the weighted mean value of winter precipitation (Goede and Hitchman, 1983; Goede *et al.*, 1986, 1990). If this situation has prevailed throughout the Quaternary the $\delta^{18}O$ record may be more appropriately interpreted as predominantly reflecting changes in winter temperatures rather than changes in mean annual temperatures.

The $\delta^{18}O$ record (Fig. 3) shows that marine Isotope Stages 3, 4 and 5 are clearly recognisable with the boundaries between them dated at 60 and 70 ka respectively. Of particular interest are two stadials each lasting less than 3 ka. Such events have been well documented from other parts of the world (Kennett and Huddlestun, 1972; Flohn, 1979; Harmon, 1980; Bond *et al.*, 1993).

The $\delta^{13}C$ record (Fig. 5) clearly shows long-term variations that are believed to reflect some kind of environmental change. These variations are clearly unrelated to any temperature changes over the time period and their interpretation is problematical. Possible influences are:

(i) The extent to which carbonate solution took place under open or closed system conditions (Hendy, 1971; Wigley, 1975).

(ii) Temporal variations in the isotopic composition of soil CO_2. In recent years strong evidence has been presented that pedogenic carbonates which, like speleothems, are deposited from seepage water that has passed through the soil, have $\delta^{13}C$ values that are directly related to the relative proportions of C_3 and C_4 plants growing at the site (Cerling *et al.*, 1989; Quade *et al.*, 1989 a, b). In speleothems such changes have also been attributed to an ecological shift between C_3 and C_4 dominated biomass reflecting a major climatic change (Talma and Vogel, 1992).

(iii) Recent evidence of a glacial–interglacial shift in the $\delta^{13}C$ composition of CO_2 in the atmosphere has come from Marino *et al.* (1992) and Leuenberger *et al.* (1992) although the magnitude of such a change remains uncertain.

(iv) Carbon isotope composition of CO_2 in the soil is also influenced by the balance between the rate of production of biogenic CO_2 within the soil and the rate of dilution with isotopically heavier (−7‰ PDB) CO_2 from the free atmosphere. It is a function of the particle size composition and moisture conditions of the soil.

Minor Element Composition

Variations in the concentrations of magnesium and strontium (Figs 6 and 7) have been correlated with the stable isotope values (Table 1). Highly significant correlations ($P << 0.001$) are found for the pairs Sr, $\delta^{18}O$ and Mg, $\delta^{13}C$, but the percentage explanation is relatively low being 37.0% for Sr/$\delta^{18}O$ and 41.5% for Mg/$\delta^{13}C$. There is little correlation between Mg and $\delta^{18}O$ ($r = 0.247$, 6.1% explanation) and virtually none between Sr and $\delta^{13}C$ ($r = 0.044$). This tends to confirm earlier work by Gascoyne (1983, 1992) who found no correlation between oxygen isotope values and magnesium content ($n = 21$) in a speleothem from northern England deposited under con-

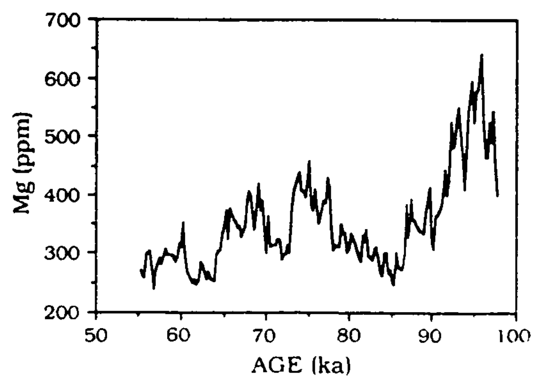

FIG. 6. Time series of magnesium content shows obvious similarities to that of the carbon isotope (Fig. 5). Like the carbon isotope series it contains two major peaks but the younger peak is much more subdued.

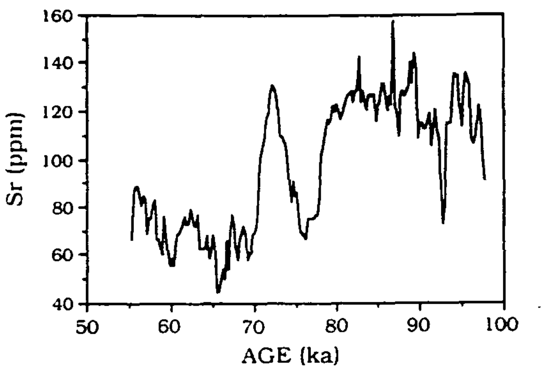

FIG. 7. Time series of strontium content shows some similarities to that of $\delta^{18}O$ values (Fig. 3). However, strontium values show a strongly bimodal frequency distribution. Another obvious difference is that while strontium values rise only slightly after 60 ka, $\delta^{18}O$ values rise rapidly almost to present day levels.

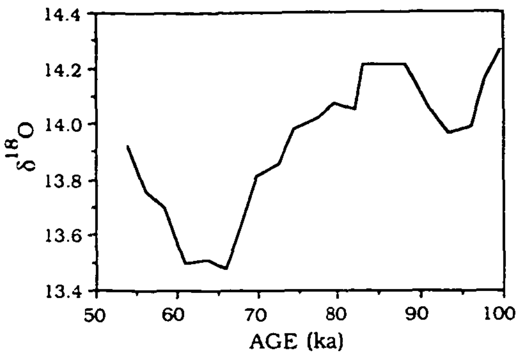

FIG. 8. Time series of oxygen isotope values from subaqeous vein calcite in Devils Hole, Nevada for the period 100 to 50 ka based on continuous sampling at 1.26 mm intervals each representing an average time interval of 1800 years (Winograd *et al.*, 1992). This record should be compared with Fig. 3. In both series there is a positive relationship between oxygen isotope values and temperature. The Devils Hole series has inadequate resolution to detect short-lived climatic events due to the extremely slow accumulation rate.

ditions of oxygen isotope equilibrium. It appears that despite earlier promise (Gascoyne, 1983; Goede and Vogel, 1991) magnesium content cannot be used as an indicator of palaeotemperature in speleothems. Instead the correlation coefficient is relatively low.

COMPARISON WITH OTHER RECORDS

There is a scarcity of records with a sufficiently high resolution to make a detailed comparison and few are available from the southern hemisphere.

Terrestrial Records

The longest high resolution terrestrial record of isotopic change recorded by carbonate deposition (60–566 ka) does not come from a speleothem but from a 'calcite vein' formed as a submerged spring deposit in Devils Hole, Nevada (Winograd *et al.*, 1992). The relevant portion of the record (60–100 ka) is reproduced here (Fig. 8). Like the FT record, $\delta^{18}O$ values bear a positive relationship to temperature change.

Both records show a trend of decreasing temperatures during marine Isotope Substage 5a and an early last glacial temperature minimum between 70 and 60 ka (Stage 4) followed by rapid warming (early Stage 3). There is clear evidence of a double temperature minimum in the FT record and a hint of it in the Devils Hole record despite a much lower time resolution. The Devils Hole record is more precisely dated than the FT stalagmite record and this may account for the apparent absence of isotope Substage 5b between 90 and 100 ka from the latter.

Baker *et al.* (1993) have presented a northwest European palaeoclimate curve based on growth-frequency variations of speleothem deposits. Growth-frequency in this area appears to be related primarily to palaeotemperature but to some extent is also influenced by moisture availability. This record shows a declining frequency from 100 to 65 ka with a double minimum between 65 and 80 ka. Resolution is relatively low but there is general agreement with the FT speleothem record.

High resolution oxygen isotope records from the GRIP ice core from summit, Central Greenland, have recently become available (Dansgaard *et al.*, 1993; Bond *et al.*, 1993). They show striking similarities with the FT speleothem record, particularly so if we accept that initiation of FT deposition postdates the beginning of marine Isotope Substage 5a, an event identified in the GRIP record as occurring at 83 ka. Both records show two short stadials superimposed on a declining temperature trend culminating in a temperature minimum (cf. marine Isotope Stage 4) interrupted by a short interstadial. This in turn is followed by a rapid temperature rise equivalent to the commencement of marine Isotope Stage 3. The FT record is terminated at this point but additional short stadials of similar character to the two earlier ones observed in both records are found in the GRIP record after 60 ka culminating in the Younger Dryas event. Bond *et al.* (1992) have suggested that such stadials are directly related to the 'Heinrich' events recorded in the North Atlantic deep sea cores. Some of the more recent have been shown

TABLE 1. Correlation matrix (r) of stable isotope and trace element measurements (n = 170)

	$\delta^{18}O$ (‰ PDB)	$\delta^{13}C$ (‰ PDB)	Mg (ppm)	Sr (ppm)
$\delta^{18}O$ (‰ PDB)	1	—	—	—
$\delta^{13}C$ (‰ PDB)	-0.089	1	—	—
Mg (ppm)	-0.247	0.644	1	—
Sr (ppm)	0.608	-0.044	0.186	1

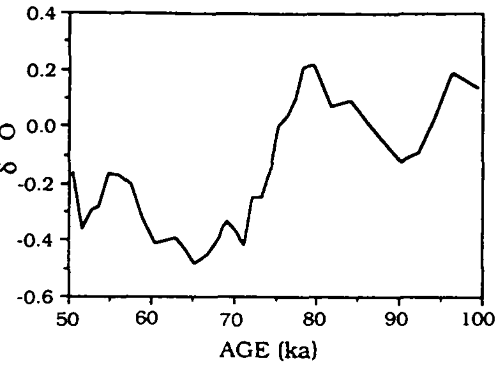

FIG. 9. A portion of the SPECMAP stacked isotope curve from 100 to 50 ka is presented here with ages of isotope events based upon the high resolution SPECMAP timescale of Martinson *et al.* (1987). Resolution is comparable to that of the Devils Hole record (Fig. 8) and will not identify short-lived climatic events due to low sedimentation rates and bioturbation in deep sea cores.

to be related to massive discharges of icebergs originating in eastern Canada.

Marine Records

The stage boundaries identified in the FT speleothem record also compare well with those determined in the high resolution SPECMAP timescale of Martinson *et al.* (1987) (Fig. 9). The boundaries between Stages 3, 4 and 5 are dated at 60 and 70 ka in the FT speleothem record (Goede *et al.*, 1990) compared with 59 and 74 ka in the SPECMAP record. The latter also shows a double minimum for Isotope Stage 4 although it must be remembered that variations in the marine oxygen isotope record are more strongly influenced by ice volume changes than by temperature changes.

Van de Geer *et al.* (*in press*) report on pollen and oxygen isotope analyses of deep sea core SO36-7SL which has provided a record from 75 to 5 ka. The core was recovered from a depth of 1085 m some 50 km from the west coast of Tasmania due west of Macquarie Harbour. The Gordon River, whose headwaters are adjacent to the Florentine Valley where Frankcombe Cave is situated, drains into Macquarie Harbour. The isotope curve records the onset of colder conditions between 75 and 70 ka but does not clearly differentiate marine Isotope Stage 4. The pollen record between 70 and 63 ka (zone 4) indicates cold conditions with a vegetation dominated by Asteraceae and grasses indicating extensive herbland with scattered open *Eucalyptus* woodland. Pollen zone 3 from 63 to 25 ka indicates some warming reflecting cool and moist conditions with a mosaic of *Eucalyptus/ Casuarina* woodland/shrubland and grassy herbland.

CONCLUSIONS

The oxygen isotope curve from the Frankcombe Cave (FT) stalagmite provides an apparently continuous high resolution record of temperature change. In Tasmania such changes are probably more appropriately interpreted

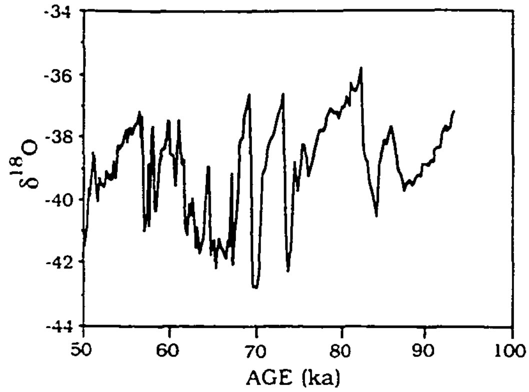

FIG. 10. The oxygen isotope record of the GRIP ice core between 94 and 50 ka from Greenland (Bond *et al.*, 1993). The GRIP record between 80 and 60 ka can be closely matched with the LT isotope record shown in Fig. 3 if the inprecise dating of the latter is taken into account and if it is accepted that LT speleothem deposition did not commence until after 80 ka as argued.

as variations in mean winter temperature rather than mean annual temperature because of the dominant contribution of winter precipitation to vadose seepage waters. The short-lived stadials identified in the record cannot be identified in deep sea cores because of low accumulation rates and the effects of bioturbation.

There is an exciting prospect that continuously sampled, high resolution palaeotemperature records from speleothems such as the FT record can be correlated with other high resolution records such as the GRIP ice core from central Greenland.

The carbon isotope record is difficult to interpret but clearly indicates long-term periodic changes that at least in part may be related to changes in dominant vegetation types. Contrary to expectations, secular variations in magnesium content are only weakly influenced by temperature changes. The highly significant correlation with $\delta^{13}C$ values may indicate a strong biogenic factor related to vegetation change.

Secular variations in strontium content show some promise of giving at least an indication of temperature conditions. Unlike the oxygen isotope ratios, strontium values show a strongly bimodal distribution reminiscent of the 'flickering switch' effect described by Taylor *et al.* (1993) for variations in the electrical conductivity of ice in the GISP2 Greenland ice core. They attribute these variations largely to fluctuations in the concentrations of calcitic dust. If some of the strontium incorporated in the FT stalagmite is of aeolian origin a similar mechanism could operate here. Dust would be carried into the Tasmanian region under interglacial conditions by strong northwesterly winds from the Australian mainland, while during glacial conditions strong zonal circulation dominated by westerly winds would cut off the sediment supply (Hesse, 1994).

Stalagmites are capable of providing a much higher resolution record than is presented here. The FT stalagmite is near the low end of the range of measured growth rates (20 to 500 mm/ka) observed in Tasmania. Also, by applying the milling technique recently used for continuous sampling of the vein calcite in Devils Hole (Winograd, 1992) it is possible to obtain samples for stable isotope mass spectrometry and trace element analysis at intervals representing only a fraction of a millimetre.

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Aminostratigraphy and electron spin resonance dating of Quaternary coastal neotectonism in Tasmania and the Bass Strait islands

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Tasmania and the Bass Strait islands (King and Flinders) preserve a widespread but fragmentary Quaternary coastal record. Quaternary coastal sediments occur in a range of morphostratigraphic settings, typically contain well-preserved and diverse molluscan fossil assemblages of shallow water origin, and provide evidence for varying degrees of neotectonic uplift over contrasting temporal and spatial scales. Holocene and Late Pleistocene (last interglacial) coastal strata occur most extensively in this region, as revealed by amino acid racemization, electron spin resonance and radiocarbon dating. Radiocarbon dates for marine molluscs from Holocene coastal strata range between 790 to 7120 a and relate specifically to the interval since the culmination of the post-glacial marine transgression. Holocene coastal sediments in this region do not provide convincing evidence for a higher sea level during the last 7000 years. The last interglacial coastal sediments in Tasmania represent the highest topographic occurrences of coastal strata of this age on the Australian continent (+11 to +32 m above present sea-level) and consistently occur above the *de facto* global 'eustatic' sea level datum of +6 m for oxygen isotope substage 5*e*. Thus, tectonic processes must be considered for their anomalously high elevation. In contrast, sediments of last interglacial age on King Island and Flinders Island do not provide evidence for uplift. Neotectonic uplift is indicated, however, by the elevation of Early and Middle Pleistocene coastal strata in this region. A southerly migration in the locus of neotectonic uplift is suggested, such that uplift occurred earlier in the Bass Strait islands than in Tasmania. The nature and precise timing of neotectonic uplift remain unresolved.

Key words: amino acid racemization, coastal sediments, electron spin resonance, last interglacial, neotectonics, Quaternary molluscs, Tasmania.

INTRODUCTION

The development of detailed records of sea-level change of presumed global applicability for the Late Quaternary (Chappell & Veeh 1978; Chappell 1983) has provided an important framework within which to study neotectonism. In particular, recent studies have examined the differential elevations of last interglacial (oxygen isotope substage 5*e*; *ca* 125 ka) coastal sequences, with a view to quantifying crustal behaviour over time scales of tens of thousands of years (Preece *et al.* 1990; Murray-Wallace & Belperio 1991; Bryant 1992). Some of the most spectacular examples of tectonically uplifted shorelines are from active plate margins such as the Huon Peninsula in Papua New Guinea and the Wanganui Basin in New Zealand (Chappell 1974; Pillans 1983; Ota *et al.* 1992). In contrast, the myth that Australia is a stable continent has been promulgated by its within-plate setting and by the widespread occurrence of 'stable' cratons, low continental gradients and ancient landscapes. This work addresses in part, the issue of the tectonic stability of the Australian coastline through a study of the Quaternary coastal record of Tasmania and the Bass Strait islands (King and Flinders). Although recent work has already challenged the notion of the tectonic stability of Australia at a continental scale (Bryant *et al.* 1988; Murray-Wallace & Belperio 1991; Bryant 1992), this paper presents a more detailed case study from the Tasmanian region in southeastern Australia and examines the significant issues raised in the study of this region's Quaternary coastal record.

Tasmania and the Bass Strait islands preserve a widespread but fragmentary Quaternary coastal record (Jennings 1959, 1961; Chick 1971; Sutherland & Kershaw 1971; Kershaw & Sutherland 1972; van de Geer *et al.* 1979; Bowden & Colhoun 1984). Coastal sediments of Pleistocene age in this region are dominated by bioclastic carbonate-quartz sands that contain diverse and well-preserved shallow water molluscan faunas. The strata typically occur as discontinuous outcrops or in shallow subcrop at varying elevations in the landscape. The sediments range from lithified to free-flowing sands and muds that have undergone varying degrees of diagenesis, reflected by their environmental settings and ages. The upper portions of some of the Pleistocene coastal strata are pedogenically modified, with calcretes present in some sections but are mainly podzolized due to leaching. The Holocene coastal record also has a fragmentary distribution. Holocene strata are of similar lithology and faunal content to their Pleistocene equivalents, but are generally unconsolidated, have undergone only minor diagenetic modification and do not require a relatively higher sea level for their deposition.

Historically, firmly establishing the ages of some of the Pleistocene coastal sequences has been difficult. Early studies for example, were unable to verify the last interglacial age attributed to many of these sequences (Jennings 1959, 1961; Sutherland & Kershaw 1971; Colhoun *et al.* 1982a, b). Relative stratigraphic relationships, geomorphologic reasoning and indirect evidence from radiocarbon dating were frequently used for age assessments (Gill & Banks 1956; Jennings 1959, 1961; van de Geer *et al.* 1979; Bowden & Colhoun 1984). Developments in Quaternary dating methods in recent years, however, have provided a means for assigning ages to the Pleistocene sequences with greater confidence.

In an earlier paper (Murray-Wallace & Goede 1991) the timing and nature of neotectonism in Tasmania was evaluated based on a study of last interglacial coastal deposits. Here, we extend the spatial and temporal coverage to include Flinders Island and King Island in Bass Strait. Further, we address the question of the duration of neotectonism in this region, through a study of the Early and Middle Pleistocene and Holocene coastal records. The aims of this work thus include: (i) to summarize the distribution of Quaternary coastal deposits in Tasmania and the Bass Strait islands, which are critical to resolving the neotectonic history of this region; (ii) to report results from amino acid racemization and electron spin resonance dating for Quaternary coastal deposits in this region; (iii) to evaluate the application of amino acid racemization and electron spin resonance for the dating of Early and Middle Pleistocene fossils; and (iv) to examine the neotectonic significance of these sequences.

METHODS

Eighteen sections containing coastal sediments of Quaternary age were studied. The oldest units examined were from Flinders Island and include the Pliocene Cameron Inlet Formation and the Early Pleistocene Memana Formation, both originally mapped near Tilba by Sutherland and Kershaw (1971; Figure 1). Seven of the Pleistocene sections were believed to be of last interglacial age (oxygen isotope substage 5*e*) based on previously established geomorphologic, palaeontologic and lithostratigraphic evidence (Jennings 1959; Sutherland & Kershaw 1971; van de Geer *et al.* 1979; Colhoun *et al.* 1982a). These included coastal deposits at Broadmeadows, Mary Ann Bay, Montagu and Mowbray Swamp in Tasmania; Egg Lagoon and Yellow Rock River on King Island and the North East River Estuary on Flinders Island (Figure 1). Seven Holocene coastal deposits were also investigated and included Shell Pits Point in Tasmania; British Admiral Beach and Three Rivers Creek Bay on King Island and Cameron Inlet, Fotheringate Bay, Sandy Lagoon and Trousers Point on Flinders Island (Figure 1). Other Holocene sites have been described by Murray-Wallace and Goede (1991). In addition, two deposits of unknown ages were examined: a deposit 3 km northwest of Reekara on King Island and The Patriarchs on Flinders Island (Figure 1). Map grid references for the sites are indicated in Table 1.

Sections of coastal sediments were measured and levelled to heights above present sea-level using either a theodolite or photogrammetric techniques. Mollusc samples were collected for dating and documentation of the faunal assemblages. Where possible, the best preserved fossils were selected for dating (e.g. specimens with chalky surfaces were excluded). Amino acid racemization, electron spin resonance and radiocarbon dating were performed on subsamples of molluscs from these deposits. Where possible, the same species was analysed by each method. Identification of molluscs is after Ludbrook (1984). Current mean annual temperatures, a relevant consideration for amino acid racemization, are 12.5°C for both Hobart and Smithton.

Amino acid racemization

Analytical procedures and sampling strategies followed those of Kimber and Griffin (1987) and Murray-Wallace and Kimber (1987). Analyses of the N-pentafluoropropionyl D, L-amino acid isopropyl esters were undertaken using a 25 m fused silica Chirasil-L-Val capillary column and Hewlett Packard model 5890A gas chromatograph with a flame ionization detector. Analyses are for the total acid hydrolysate, a complex mixture of amino acids bound in peptides of varying molecular weights and free amino acids. Results are reported for several enantiomeric amino acids that include alanine (ALA), valine (VAL), leucine (LEU), aspartic acid (ASP), phenylalanine (PHE) and glutamic acid (GLU). Results are not reported for the diastereoisomer isoleucine because of poor baseline resolution during chromatography.

Analyses were undertaken on the hinge region of fossil bivalves that include *Bassina pachyphylla*, *Cardium* sp., *Cucullaea corioensis*, *Dosinia coerulea*, *Divalucina cumingi*, *Fulvia tenuicostata*, *Glycymeris striatularis*, *Katelysia scalarina*, *K. rhytiphora*, *Mactra australis*, and *Pecten meridionalis*. In the case of the limpet, *Patella laticostata*, the central growth region was analysed. Molluscs characterized by moderate racemization rates (Wehmiller 1984a; Miller & Brigham-Grette 1989) were selected in this study. The integrity of the analytical procedures was evaluated by analysing international, interlaboratory comparison samples of Wehmiller (1984b). All results were within two standard deviations of the grand mean of the international comparison.

Three amino acid racemization analyses were also undertaken on the hydrochloric acid residues from the carbon dioxide evolution procedure of radiocarbon sample preparation (samples SUA-2925, SUA-2926 and SUA-2927). This provided a direct comparison between amino acid racemization and radiocarbon dating for a Late Pleistocene and two Holocene samples and follows the procedure outlined by Murray-Wallace and Bourman (1990).

Electron spin resonance

Electron spin resonance and its application to dating has been discussed by Ikeya (1988), Goede (1988) and Grün (1989). Details of sample preparation for shell dating are provided by Goede and Hitchman (1987) and Goede (1989).

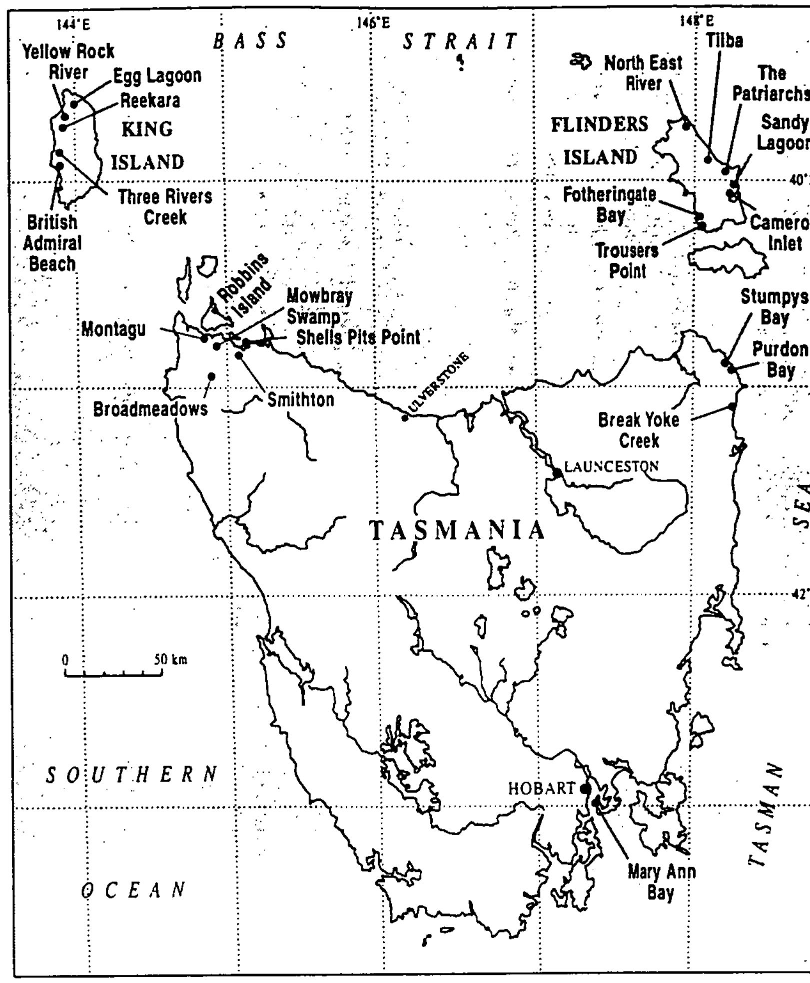

Figure 1 Location map of sample sites in Tasmania, King Island and Flinders Island.

Electron spin resonance analyses were carried out on a JOEL JES FE3X ESR spectrometer at ambient temperatures and at 100 kHz using a 4×10^{-5} T field modulation, an amplitude of 10^3 and a microwave power of 5 mW. The spectral peak at g = 2.0008 was used for the determination of equivalent dose values. Equivalent dose values represent an estimate of the radiation dose a sample has received since death and incorporation in sediments. All but one of the samples (sample T6) were composed of aragonite. In the case of one calcite shell, a sample of *Pecten meridionalis*, the presence of Mn^{2+} lines in the spectrum was found to interfere with the spectral peak used for dating. The problem was overcome using the technique of Ninagawa *et al.* (1985). Multiple measurements of the dating peak were made for each of the sub-samples and regression analysis was used to calculate the gamma equivalent dose of the sample using the procedure advocated by Franklin (1986). Molluscs analysed include *Bassina pachyphylla, Cellana solida, Cucullaea corioensis, Divalucina cumingi, Dosinia coerulea, Fulvia tenuicostata, Glycymeris radians, G. striatularis, Katelysia rhytiphora, K. scalarina, Paphies erycinaea, Pecten meridionalis, Soletellina biradiata* and *Turbo undulatus*.

Radiocarbon dating

In view of the difficulty of reliably dating marine molluscs by the uranium-series disequilibrium method, radiocarbon dating was undertaken on selected mollusc samples to calibrate the results of amino acid racemization and electron spin resonance. Radiocarbon dating procedures followed the methods outlined by Gupta and Polach (1985). The Holocene radiocarbon dates for molluscs were corrected for the 'reservoir-effect' for southern Australian ocean surface waters (−450 ± 35 a) and converted to sidereal years (Gillespie & Polach 1979; Stuiver *et al.* 1986).

Table 1 Summary of Quaternary coastal deposits from Tasmania and Bass Strait islands examined in this study.*

Locality	Map grid reference†	Sediment type and colour	Facies	Dominant mollusca	Depth of burial (m)	Elevation AHD (m)	Previously inferred age	References
Pleistocene deposits								
Mary Ann Bay, Tasmania	322417[a]	Shell-rich quartz sand (5Y 6/4)	Lower shoreface sand	*Pecten meridionalis*, *Equichlamys bifrons*	2	24.6	Last interglacial	Colhoun *et al.* (1982a); Murray-Wallace and Goede (1991)
Montagu, Tasmania	274829[b]	Shell-rich quartz sand (5Y 6/1)	Embayment fill	*Glycymeris striatularis*, *Fulvia tenuicostata*	2	12.3	Last interglacial	Colhoun *et al.* (1982a); Murray-Wallace & Goede (1991)
Broadmeadows, Tasmania	366730[c]	Shell-rich quartz sand (N5)	Embayment fill	*G. striatularis*	2	14.3	Last interglacial	Colhoun *et al.* (1982a); Murray-Wallace & Goede (1991)
Mowbray Swamp, Tasmania	362755[c]	Shell-rich quartz sand (5YR 6/1)	Embayment fill	*G. striatularis*, *Mactra jacksoniensis*	6–9	12.3	Last interglaical	Gill and Banks (1956); Murray-Wallace & Goede (1991)
Yellow Rock River, King Island	330002[d]	Skeletal carbonate sand (10YR 6/6)	Estuarine sand flat	*Katelysia* sp.	1	3.7	Last interglacial	Jennings (1959)
Egg Lagoon, King Island	409063[d]	Skeletal carbonate sand	Estuarine fill	*Katelysia* sp.	8.2–9.8 and 10.3–10.5	*ca* 6	Last interglacial	Jennings (1959)
North East River, Flinders Island	819997[e]	Shell-rich skeletal carbonate sand (5Y 8/4)	Estuarine sand flat	*K. rhytiphora*, *Batillaria* sp., *Notospisula trigonella*	1–2	4.5	Last interglacial	Sutherland and Kershaw (1971) This study
Holocene								
Shell Pits Point, Tasmania	430806[c]	Coquina	Beach ridge	*G. striatularis*, *K. rhytiphora*, *F. tenuicostata*, *Placamen placida*	0.3	≤ 1	Holocene, *Fulvia tenuicostata*, 7120 ± 70 (SUA-2928)	
British Admiral Beach, King Island	316730[d]	Cobble-shingle sand (5Y 7/2)	Cobble-shingle storm beach	Comminuted mixed-species assemblage	3	2.7	Holocene, mixed species, 4560 ± 120 (SUA-2926)	This study

Table 1 (*Continued.*)

Locality	Map grid reference[a–e]	Sediment type and colour	Facies	Dominant mollusca	Depth of burial (m)	Elevation AHD (m)	Previously inferred age	References
Three Rivers Creek, King Island	299789[d]	Shingle-gravel	Shingle storm beach	*Patella laticostata*, *Turbo undulatus*	3	1.7	Holocene, *Patella* sp. 790 ± 60 (SUA-2927)	This study
Cameron Inlet, Flinders Island	062603[e]	Shell-rich muddy sand (10YR 4/2)	Back-barrier lagoon	*Katelysia* sp.	0.3–0.6	0.5	Holocene, *Katelysia* sp., 3600 ± 110 (SUA-3001)	This study
Sandy Lagoon, Flinders Island	059608[e]	Shell-rich muddy sand	Back-barrier lagoon	*Katelysia* sp., *Batillaria diemenensis*	0.1	0	Holocene, *Katelysia* sp., 2060 ± 100 (SUA-3015)	This study
Fotheringate Bay, Flinders Island	888492[e]	Shelly sand (10YR 4/6)	Embayment fill	*K. scalarina*, *Mactra pura*, *B. diemenensis*	0.1	0	Holocene, *K. scalarina*, 5580 ± 80 (SUA-3010)	This study
Trousers Point Beach, Flinders Island	880464[e]	Quartzose-carbonate sand (10YR 6/2)	Back-barrier lagoon	*Katelysia* sp.	0.2	0	Holocene, *Katelysia* sp., 3580 ± 90 (SUA-3002)	This study
Deposits of previously unknown age								
The Patriarchs, Flinders Island	033720[e]	Muddy quartzose sand	Sand flat	*K. rhytiphora*, *Batillaria* sp.	0.4	2.1	?	-
Reekara, King Island	329967[d]	Shelly sand	?	*Katelysia* sp.	3–4	*ca* 18	?	-

*The Pliocene Cameron Inlet Formation and Early Pleistocene Memana Formation from Flinders Island are not included in this summary.
[a–e] a–e: Tasmania 1:100 000 topographic map series. [a]Sheet 8312, Edition 1; [b]Sheet 7816, Edition 1; [c]Sheet 7916, Edition 1; [d]Parts of sheets 7617, 7618, 7717 and 7718, Edition 1; and [e]Sheet 8517, Edition 3.

PLIO-PLEISTOCENE COASTAL DEPOSITS

Pliocene Cameron Inlet Formation, Flinders Island

Shallow-water coastal sediments assigned to the Pliocene Cameron Inlet Formation were mapped by Sutherland and Kershaw (1971) along the eastern coastal plains of Flinders Island. The type locality is situated in Nelsons Drain, approximately 4 km west of Sandy Lagoon (Figure 1). However, here it is poorly exposed and reveals only a 0.6 m thick unit of green glauconitic shelly marl with numerous molluscs including disarticulate *Cucullaea* sp. Elsewhere, the formation is revealed in waterholes, quarries, drains and boreholes. A Middle to Late Pliocene age was assigned to the Cameron Inlet Formation based on the presence of the echinoid *Lovenia*, known elsewhere in Tertiary deposits in southern Australia and the bivalve *Cucullaea* sp. (Sutherland & Kershaw 1971).

Specimens of *Bassina pachyphylla, Cucullaea* sp., *Glycymeris* sp. and *Katelysia scalarina* were selected for amino acid racemization and electron spin resonance dating. Samples were obtained from a recently excavated waterhole at the roadside on Melrose Road (Table 1). The molluscs were obtained from a 3 m thick unit of light grey (10YR 8/2) shelly sand that occurs beneath a thin (20 cm) soil. The upper bounding surface of the shell bed is some 9.7 m above present sea level. The formation also crops out at 18 m above present sea level along the eastern side of Wingaroo Road (grid reference 855826, Tasmania 1:100 000 topographic map, land tenure index series, sheet 8517, edition 3).

EARLY PLEISTOCENE

Memana Formation, Flinders Island

The Memana Formation refers to fossiliferous shelly sand that crops out and is revealed in shallow excavations, to the north of The Patriarchs, along the northeastern coastal plain of Flinders Island (Sutherland & Kershaw 1971). The formation is distinguished from the Cameron Inlet Formation by the presence of the bivalve mollusc *Zenatiopsis ultima* which, according to Darragh and Kendrick (1971), suggests an Early Pleistocene age (Werrikooian) for the formation. Some *remanie* Pliocene shells also occur within the basal portion of the Memana Formation (Sutherland & Kershaw 1971). The presence of well-preserved individuals of the gastropod *Bankivia fasciata* indicates that the Memana Formation is of shallow water origin (i.e. water depth < 5 m; Ludbrook 1984).

Specimens of *Divalucina cumingi, Dosinia coerulea, Glycymeris striatularis* and *Katelysia rhytiphora*, selected for amino acid racemization and electron spin resonance dating, were obtained from a section of the Memana Formation within a waterhole at Tilba (Figure 1; Table 1). The excavation revealed a basal unit (40 cm) of sparsely fossiliferous, light grey (10YR 8/2) medium-grained quartz-carbonate sand (Figure 2). Molluscs included species typical of shallow-water settings (i.e. intertidal to shallow subtidal) and included the bivalves *Divalucina cumingi, Dosinia coerulea, Fulvia tenuicostata, Glycymeris striatularis, Katelysia rhytiphora, Mactra* sp. and *Ostrea* sp. The top of the shelly sand occurs at 11.2 m above present sea level.

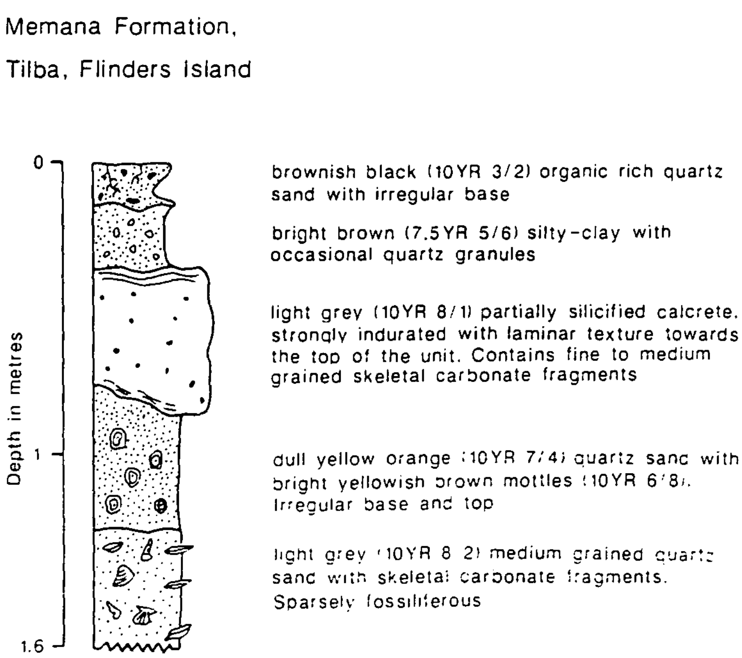

Figure 2 Measured section of the Early Pleistocene Memana Formation at Tilba on Flinders Island.

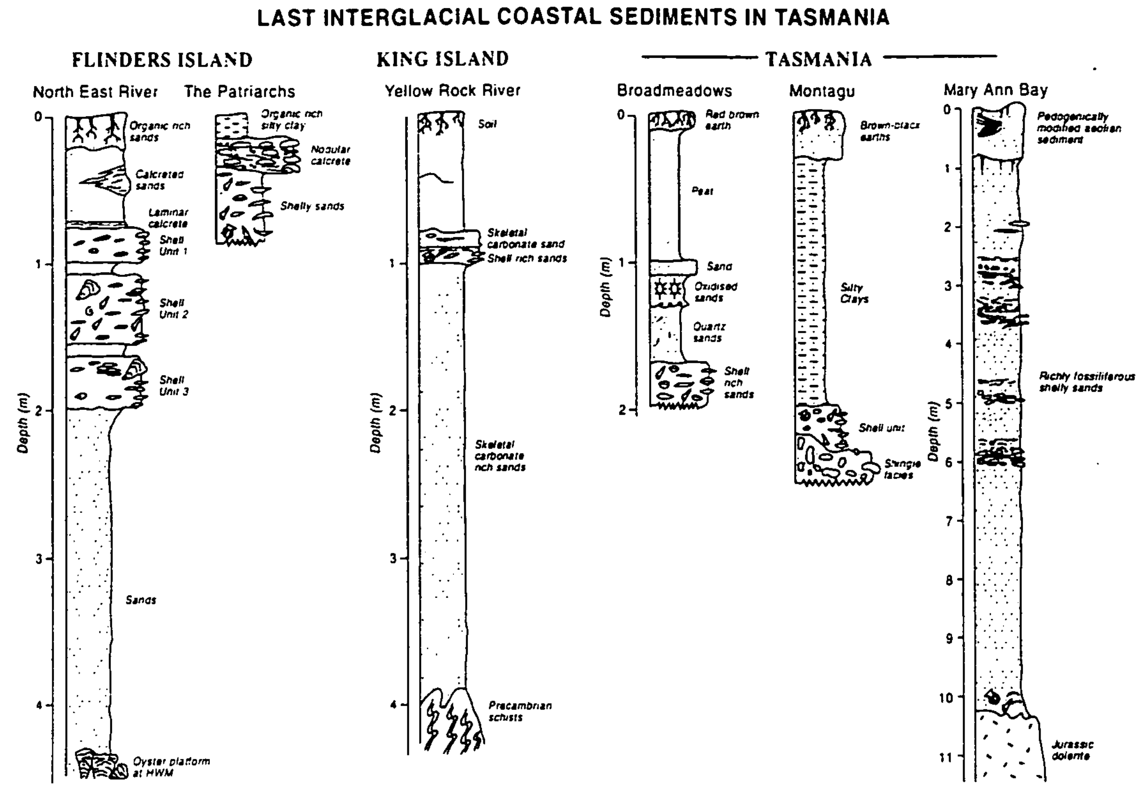

Figure 3 Measured sections through Late Pleistocene (last interglacial: oxygen isotope substage 5*e*) coastal sediments in Tasmania, King Island and Flinders Island.

LATE PLEISTOCENE

Pleistocene coastal sediments previously assigned to the last interglacial (oxygen isotope substage 5*e*) in Tasmania include deposits at Mary Ann Bay near Hobart and at Broadmeadows, Montagu and Mowbray Swamp on the northwest coast of the island (Colhoun *et al.* 1982a; Murray-Wallace & Goede 1991; Figure 1). A last interglacial age has also been assigned to several deposits on the Bass Strait islands including Yellow Rock River and Egg Lagoon on King Island (Jennings 1959) and a deposit in the North East River Estuary on Flinders Island (Sutherland & Kershaw 1971). The stratigraphy of Egg Lagoon is summarized by D'Costa *et al.* (1993). Molluscs present in all these sequences are extant and frequent intertidal and shallow subtidal settings (Colhoun *et al.* 1982a; Ludbrook 1984).

Several factors led to a last interglacial age being provisionally assigned to these coastal deposits. In Tasmania, the elevation of the strata above present sea level is generally too high for them to be regarded as Holocene (i.e. typically > 11 m above present sea level). In addition, preliminary radiocarbon assays on peat and marl that overlie the marine sand, and on molluscs from the Tasmanian coastal deposits, yielded dates older than Holocene. In general, radiocarbon dating of Pleistocene materials yielded 'finite' ages close to the practical limits of the radiocarbon method (Gill & Banks 1956; Colhoun *et al.* 1982b; van de Geer *et al.* 1986). A radiocarbon date of > 52 ka (GrN-9743) on overlying peat from Mowbray Swamp (van de Geer *et al.* 1986) indicates that the previously reported 'finite' ages reflect contamination by varying amounts of ^{14}C with a higher (younger) activity that could not be isolated during sample pretreatment. Other evidence consistent with a Late Pleistocene age centres on the morphostratigraphic, biostratigraphic and diagenetic character of the strata (Bowden & Colhoun 1984) in conjunction with an event-stratigraphic framework of Late Quaternary glacio–eustatic sea level change (Chappell & Veeh 1978; Chappell 1983). The general lithostratigraphic and geomorphologic setting of the Late Pleistocene coastal deposits are summarized in Table 1 and Figure 3. Additional, more detailed lithostratigraphic descriptions are presented by Colhoun *et al.* (1982a) and Murray-Wallace and Goede (1991).

HOLOCENE

Holocene coastal deposits occur extensively but discontinuously around the coastlines of Tasmania, Flinders Island and King Island (Jennings 1959; Sutherland & Kershaw 1971; Kershaw & Sutherland 1972; van de Geer 1981; Murray-Wallace & Goede 1991). Deposits include sediments formed in high- and low-wave energy settings reflected by the presence of cobble-shingle gravel beaches and back-barrier lagoon and embayment fills, respectively

The strata are typically unconsolidated and have undergone minimal pedogenic or diagenetic modification. The deposits generally contain diverse and well-preserved molluscan fossil assemblages that indicate only a shallow-water cover during deposition. The strata do not indicate a higher sea-level than the present time during the Holocene. A summary of the general characteristics of the Holocene coastal deposits is summarized in Table 1. More detailed lithostratigraphic descriptions are provided elsewhere (Jennings 1959; Sutherland & Kershaw 1971; Kershaw & Sutherland 1972; Murray-Wallace & Goede 1991).

RESULTS

Radiocarbon dating

Radiocarbon dating of molluscs from coastal deposits independently ascribed to the Late Pleistocene yielded 'finite' dates in excess of 30 ka. Dating of five whole disarticulated valves of the scallop *Pecten meridionalis* from Mary Ann Bay in Tasmania yielded a finite radiocarbon age of 39 900$^{+800}_{-700}$ a (SUA-2925). Similarly, a radiocarbon age of 31 100 ± 300 a (SUA-3000) was obtained on specimens of the cockle *Katelysia* sp. from the North East River Estuary on Flinders Island. The extent of racemization for a range of amino acids and the electron spin resonance equivalent dose values are too high for these radiocarbon ages to be regarded as accurate (cf. Murray-Wallace *et al.* 1993). These radiocarbon dates are therefore interpreted as 'minimum ages' that reflect varying degrees of contamination, equivalent to the incorporation of 1-3% ^{14}C with a modern activity, that could not be removed during radiocarbon sample pretreatment. The dates are significant, however, for they indicate that these two deposits are not Holocene. In contrast, radiocarbon dating of Holocene molluscs yielded ages consistent with their morphostratigraphic context. The ages range from 790 to 7120 a and relate specifically to the interval since the culmination of the post-glacial marine transgression in southern Australia (Thom & Chappell 1975; Table 1).

Amino acid racemization dating

The relative extent of racemization for all amino acids in the Pleistocene and Holocene fossil molluscs is in accord with published results (e.g. Lajoie *et al.* 1980) and generally follows the relation VAL< GLU< LEU< PHE < ASP<< ALA (Table 2). Exceptions, however, include higher extents of racemization for leucine than phenylalanine in *Katelysia* sp. from Egg Lagoon (Table 2). An apparent reversal in the extent of aspartic acid racemization is also evident for the Pliocene molluscs from the Cameron Inlet Formation (Table 2). Kimber *et al.* (1986) observed this phenomenon in high-molecular weight peptides in laboratory experiments that simulated diagenetic racemization at elevated temperatures. They attributed this to the influence of progressive hydrolysis on peptides that contain hydrophobic amino acids bound in internal positions.

Amino acid data reported for each site represent mean values for several sample replicates. Coefficients of variation ([SD/mean$_{D/L}$] × 100%) for intershell amino acid D/L ratio variation are generally less than 15% (Table 2). An example of concordant results for intershell and intersite amino acid D/L ratio variation is illustrated for the amino acid valine, for molluscs of last interglacial age (Figure 4). The larger scatter of data for The Patriarch deposit on Flinders Island may have resulted from a shallow depth of burial, such that diurnal and seasonal fluctuations assumed greater significance during diagenesis than for more deeply buried fossils. Despite this, a last interglacial age is assigned to this deposit

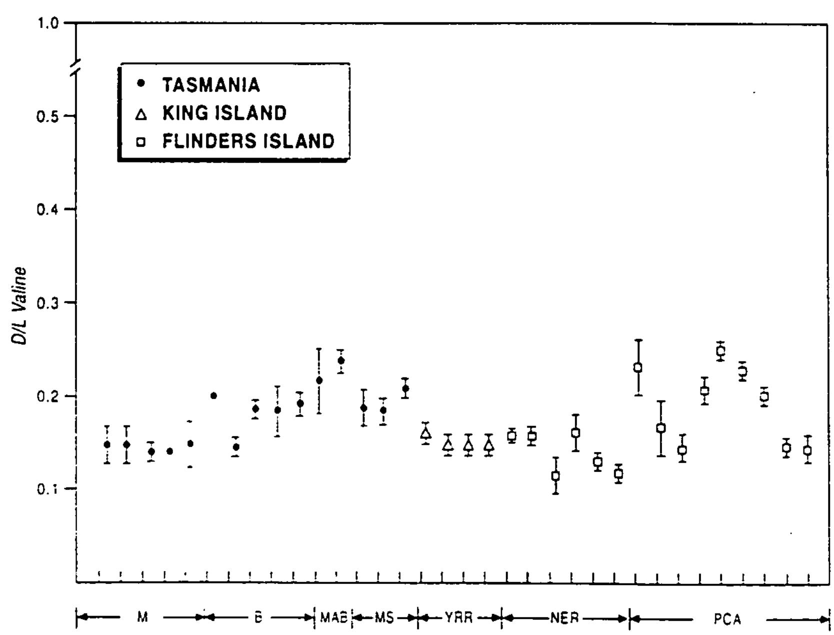

Figure 4 Extent of racemization (total acid hydrolysate) for the amino acid valine for mollusc sample replicates from last interglacial coastal sediments in Tasmania, King Island and Flinders Island. Sample localities: M, Montagu; B, Broadmeadows; MAB, Mary Ann Bay; MS, Mowbray Swamp; YRR, Yellow Rock River; NER, North East River and PCA, The Patriarchs (refer to Figure 1 for locations).

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Table 2 Summary of amino acid racemization data from Tasmania and Bass Strait islands.

Locality	Species	Amino acid D/L ratio						Age
		ALA	VAL	LEU	ASP	PHE	GLU	
Shell Pits Point, Tas.	*Glycymeris striatularis*	–	0.09 ±0.002 (2.2)	0.17 ± 0.01 (5.9)	–	0.16 ± 0.05 (31.2)	0.15 ± 0.004 (2.6)	Holocene
Three Rivers Creek, KI	*Patella laticostata*	0.07 ± 0.01 (14.3)	0.01	0.05 ± 0.02 (40.0)	–	0.04 ± 0.001 (2.5)	0.05 ± 0.001 (2.0)	Holocene
British Admiral Beach, KI	Mixed species assemblage	0.18 ± 0.01 (5.5)	0.05 ± 0.004 (8.0)	0.12 ± 0.004 (3.3)	–	0.14 ± 0.002 (1.4)	0.12 ± 0.002 (1.7)	Holocene
Mary Ann Bay, Tas.	*Fulvia tenuicostata*		0.22 ± 0.04 (18.2)	0.39 ± 0.02 (5.2)	0.36 ± 0.02 (5.6)		0.26 ± 0.04 (15.4)	Last interglacial
Mary Ann Bay, Tas.	*Pecten meridionalis*	–	0.24 ± 0.01 (4.2)	0.27 ± 0.002 (1.0)	0.44 ± 0.004 (1.0)	0.49 ± 0.01 (2.0)		Last interglacial
Montagu, Tas.	*F. tenuicostata*	–	0.15 ± 0.002 (1.3)	0.35 ± 0.05 (14.3)	0.37 ± 0.04 (10.8)	0.47 ± 0.05 (10.6)	0.19 ± 0.03 (15.8)	Last interglacial
Montagu, Tas.	*Glycymeris striatularis*	–	0.15 ± 0.007 (5.0)	0.30 ± 0.01 (3.3)	0.47 ± 0.06 (12.8)	0.39 ± 0.03 (7.7)	0.20 ± 0.004 (2.0)	Last interglacial
Broadmeadows, Tas.	*G. striatularis*	–	0.18 ± 0.02 (11.1)	0.31 ± 0.04 (12.9)	0.49 ± 0.06 (12.2)	0.43 ± 0.05 (11.6)	0.25 ± 0.01 (4.0)	Last interglacial
Mowbray Swamp, Tas.	*G. striatularis*		0.20 ± 0.02 (10.0)	0.47 ± 0.03 (6.4)	0.53 ± 0.03 (5.7)	0.47 ± 0.06 (12.8)	0.27 ± 0.02 (7.4)	Last interglacial
Yellow Rock River, KI	*Katelysia rhytiphora*		0.15 ± 0.01 (6.7)		0.54 ± 0.01 (2.0)	0.29 (?)	0.24 ± 0.01 (4.2)	Last interglacial
Yellow Rock River, KI	*K. scalarina*	–	0.15 ± 0.002 (1.3)		0.53 ± 0.02 (3.8)	0.24 (?)	0.23 ± 0.02 (8.7)	Last interglacial
North East River, FI	*K. rhytiphora*	–	0.14 ± 0.02 (14.3)	0.36 ± 0.05 (13.9)	0.59 ± 0.06 (10.2)	0.37 ± 0.03 (8.1)	0.25 ± 0.02 (8.0)	Last interglacial
The Patriarchs, FI	*F. tenuicostata*	–	0.15 ± 0.02 (13.3)	0.31 ± 0.02 (6.5)	0.44 ± 0.03 (6.8)	0.31 ± 0.09 (29.0)	0.25 ± 0.04 (16.0)	Last interglacial
The Patriarchs, FI	*K. rhytiphora*	–	0.25 ± 0.05 (20.0)	–	0.64 ± 0.03 (4.7)	0.49 ± 0.11 (22.4)	0.35 ± 0.02 (5.7)	Last interglacial
Reekara, KI	*K. rhytiphora*	0.68 ± 0.04 (5.9)	0.40 ± 0.02 (5.0)	–	0.63 ± 0.03 (4.8)	–		Middle Pleistocene
Egg Lagoon, KI	*K. scalarina*	0.84 ± 0.01 (1.2)	0.55 ± 0.001 (0.2)	0.86 ± 0.02 (2.3)	0.77 ± 0.002 (0.3)	0.73 ± 0.01 (1.4)	0.61 ± 0.001 (0.2)	Early Pleistocene
Egg Lagoon, KI	*K. rhytiphora*	0.81 ± 0.02 (2.5)	0.51 ± 0.004 (1.0)	0.70 ± 0.03 (4.3)	0.76 ± 0.003 (0.4)	0.64 ± 0.02 (3.1)	0.55 ± 0.04 (7.3)	Early Pleistocene
Memana Formation, Tilba, KI	*K. rhytiphora*	0.78 ± 0.07 (8.9)	0.45	0.58 ± 0.18 (31.0)	0.78 ± 0.01 (1.3)	0.84 ± 0.09 (10.7)	0.53 ± 0.01 (1.9)	Early Pleistocene
Memana Formation, Tilba, KI	*Divalucina cumingi*	0.91 ± 0.02 (2.2)	–	–	0.96 ± 0.01 (1.0)	0.93 ± 0.01 (1.1)	0.77 ± 0.01 (1.3)	Early Pleistocene
Cameron Inlet Formation, Melrose Road, FI	*K. scalarina*	0.69 ± 0.16 (23.2)	0.52 ± 0.08 (15.4)	0.49 ± 0.06 (12.2)	0.71 ± 0.02 (2.8)	0.65 ± 0.14 (21.5)	0.63 ± 0.10 (15.8)	Pliocene
Cameron Inlet Formation, Melrose Road, FI	*G. striatularis*	0.76 ± 0.09 (11.8)	0.49 ± 0.08 (16.3)	0.71 ± 0.09 (12.7)	0.56 ± 0.10 (17.8)	0.62 ± 0.16 (25.8)	0.58 ± 0.09 (15.5)	Pliocene
Cameron Inlet Formation, Melrose Road, FI	*Dosinia coerulea*	0.78 ± 0.07 (8.9)	0.52 ± 0.06 (11.5)	0.66 ± 0.01 (1.5)	0.84 ± 0.01 (1.2)	0.84 ± 0.09 (10.7)	0.78 ± 0.02 (2.6)	Pliocene

Localities: Tas, Tasmania; FI, Flinders Island; KI, King Island.
Amino acids: ALA, alanine; VAL, valine; LEU, leucine; ASP, aspartic acid; PHE, phenylalanine; and GLU, glutamic acid.
Numbers in parentheses indicate coefficients of variation: see text.

based on amino acid racemization, as the mean D/L ratio for valine (0.20 ± 0.07; $n = 2$) is not significantly different to the grand mean for all the other last interglacial sample sites excluding The Patriarchs (0.18 ± 0.04; $n = 9$). Calculation of a z-score following the procedure of Gupta and Polach (1985) indicates that these two data sets are not significantly different at the 5% level ($z = 0.248$).

The extent of amino acid racemization is consistently greater in the molluscs from deposits attributed last interglacial ages than for all the Holocene samples including those from Shell Pits Point, Three Rivers Creek Bay and British Admiral Beach that have been independently dated using radiocarbon (see also Murray-Wallace & Goede 1991). In contrast, the extent of racemization for a range of amino acids in the last interglacial molluscs is consistently lower than observed in their Pliocene and Early Pleistocene equivalents (Table 2). The similarity in the extent of racemization for all amino acids in the last interglacial molluscs indicates a common age for the different deposits given the assumption that the integrated effect of all the parameters likely to influence racemization between the sample sites was comparable during diagenesis. This assumption is supported by the excellent and similar preservation states of the molluscs, the absence of recrystallization from metastable aragonite to calcite and that the molluscs from each deposit, with the exception of The Patriarchs, were well buried and do not appear to have been subaerially exposed during diagenesis.

In contrast, greater scatter in enantiomeric ratios is evident for the samples independently ascribed Pliocene and Early Pleistocene ages. Despite this higher variation, results clearly indicate that these deposits are substantially older than Late Pleistocene, and appear to be consistent with the biostratigraphic evidence previously advanced for their antiquity. Greater concordance of results for intershell D/L ratio variation is evident, however, for the *Katelysia* sp. from Egg Lagoon on King Island. A minimum age of Early Pleistocene (undifferentiated) is suggested. The extent of racemization for a range of amino acids is consistently greater in the Egg Lagoon samples than for molluscs from the other deposits, independently assigned to the last interglacial (Table 2). Further, the extent of racemization for a range of amino acids in *Katelysia scalarina* from Egg Lagoon is similar to that recorded for *Katelysia* sp. from the Plio/Pleistocene strata of Flinders Island. These data therefore challenge the lithostratigraphic correlation made by Jennings (1959) for the basal shell bed at Egg Lagoon with sediments of similar lithology and of inferred last interglacial age at Yellow Rock River on King Island. The specimens of *K. rhytiphora* from Reekara on King Island appear to be younger than the Egg Lagoon samples, based on the lower extent of racemization and also on the electron spin resonance data. Although more data are required, the molluscs from Reekara are provisionally assigned to the Middle Pleistocene.

Although the extent of racemization for a range of amino acids in molluscs from the Pliocene Cameron Inlet Formation and the Early Pleistocene Memana Formation is significantly greater than that observed for the last interglacial data set, the results appear lower than would normally be expected for fossils of this age (cf. Murray-Wallace & Kimber 1989). Generally, a lower concordance of results for the extent of racemization in sample replicates is also evident for these two amino acid data sets, than for the Late Pleistocene and Holocene examples. One explanation for this may involve the preferential loss of the more extensively racemized amino acids that are bound in lower molecular weight peptides as well as the free amino acids. This would lower the extent of racemization for the total acid hydrolysate and a possible mechanism for this phenomenon may involve *in situ* leaching, a process previously identified in last interglacial specimens of the benthic foraminifer *Marginopora vertebralis* from Wardang Island, South Australia (Murray-Wallace & Belperio 1994).

Electron spin resonance dating

The results of the electron spin resonance analyses are shown in Table 3. Both in Tasmania and the Bass Strait islands, molluscs from Holocene coastal deposits consistently yield equivalent dose (ED) values that are between 0 and 30 gray (Table 3). In contrast, deposits assigned to the last interglacial show greater variation. Coastal sediments of this age in the Bass Strait islands are characterized by a calcareous matrix and the shells have consistently yielded ED values in the range of between 100 and 250 gray. These values are also in accord with results from other last interglacial sites in southern Australia and southern Africa (Hewgill *et al.* 1983; Goede & Hitchman 1987; Goede 1989; Figure 5). Tasmanian sites of equivalent age are characterized by a siliceous matrix and shells exhibit ED values that tend to cluster between 60 and 120 gray (Figure 6) and are attributed here to the low concentration of radioactive elements in the fossil matrix.

At all but one site electron spin resonance analyses support the last interglacial ages assigned on the basis of independent geologic evidence and amino acid racemization. The exception is The Patriarchs deposit, where for three specimens, significantly higher ED values were obtained than typify deposits of last interglacial age (Figure 5). To test whether this is due to uranium enrichment of the shells, uranium analyses were undertaken on all samples (Table 3). The uranium content of the two samples of *Fulvia tenuicostata* (FL9 and 12) at The Patriarchs is not as high as that of samples of the same species at Mary Ann Bay (F54 and F56) and at Montagu (T8) yet the ED values are much greater. The Patriarchs samples are either older or they and the surrounding matrix are enriched in other radioactive elements such as potassium and thorium. The Patriarchs deposit differs from all others reported here by being in close proximity to the colluvial footslope of the granite monadnock after which the site is named. Not only would the site receive runoff from the monadnock after heavy rain, but the shells are also closely associated with a blocky calcrete that may be enriched in radioactive elements derived from chemical weathering of the granite. The shallow depth of burial of the shells will also have

Table 3 Summary of electron spin resonance data from Tasmania and Bass Strait islands.

Locality	Sample no.	Species	ED (grey)	Uranium content (ppm)	95% Confidence limits
Holocene					
Shell Pits Point, Tas.	T10	*Fulvia tenuicostata*	26	1.5	21-30
Shell Pits Point, Tas.	T16	*Katelysia rhytiphora*	18	1.0	14-21
Cameron Inlet, FI	FL8	*K. rhytiphora*	11	2.5	5-17
Sandy Lagoon, FI	FL26	*K. rhytiphora*	24	ND	21-27
Fotheringate Bay, FI	FL27	*Soletellina biradiata*	8	ND	1-15
Trousers Point Beach, FI	FL6	*K. scalarina*	10	0.8	6-13
Trousers Point Beach, FI	FL7	*K. scalarina*	16	0.8	14-18
British Admiral Beach, KI	K13	*Turbo undulatus*	22	0.2	0-89
British Admiral Beach, KI	K23	*T. undulatus*	11	0.2	1-21
Three Rivers Creek Bay, KI	K18	*Cellana solida*	24	<0.2	0-101
Three Rivers Creek Bay, KI	K27	*T. undulatus*	6	0.2	2-14
Last Interglacial (Late Pleistocene)					
Montagu, Tas.	T8	*F. tenuicostata*	102	2.2	91-116
Montagu, Tas.	T11	*Glycymeris striatularis*	66	0.8	60-71
Montagu, Tas.	T30	*G. striatularis*	63	0.6	59-68
Montagu, Tas.	F55	*F. tenuicostata*	93	0.8	86-101
Montagu, Tas.	F57	*F. tenuicostata*	84	0.8	77-92
Mowbray Swamp, Tas.	T13	*G. striatularis*	72	1.7	67-77
Mowbray Swamp, Tas.	T18	*Paphies erycinaea*	76	1.1	70-81
Broadmeadows, Tas.	T14	*G. striatularis*	94	1.4	83-105
Broadmeadows, Tas.	T29	*Tucetona flabellatus*	81	0.7	75-87
Mary Ann Bay, Tas.	F54	*F. tenuicostata*	145	2.4	128-166
Mary Ann Bay, Tas.	F56	*F. tenuicostata*	112	2.4	102-123
Mary Ann Bay, Tas.	T6	*Pecten meridionalis*	104	0.6	94-116
Yellow Rock River, KI	K24	*F. tenuicostata*	236	0.6	205-272
Yellow Rock River, KI	K25	*K. scalarina*	121	0.4	114-129
North East River, FI	FL2	*K. rhytiphora*	148	0.8	141-155
North East River, FI	FL3	*K. rhytiphora*	145	0.6	128-164
North East River, FI	FL4	*F. tenuicostata*	190	1.5	183-197
North East River, FI	FL5	*F. tenuicostata*	183	0.8	149-225
The Patriarchs, FI	FL9	*F. tenuicostata*	415	1.3	318-544
The Patriarchs, FI	FL10	*K. rhytiphora*	540	1.5	455-637
The Patriarchs, FI	FL11	*Divalucina cumingi*	241	0.6	219-253
The Patriarchs, FI	FL12	*F. tenuicostata*	681	1.7	653-708
Early Pleistocene, Memana Formation, Flinders Island					
Tilba, FI	FL13	*D. cumingi*	1086	0.8	-
Tilba, FI	FL14	*Dosinia coerulea*	1776	2.5	-
Tilba, FI	FL15	*K. rhytiphora*	2263	1.1	-
Pliocene, Cameron Inlet Formation, Flinders Island					
Melrose Road, FI	FL16	*Cucullaea corioensis*	∞	<0.2	-
Melrose Road, FI	FL17	*Bassina pachyphylla*	∞	2.5	-
Melrose Road, FI	FL18	*D. coerulea*	∞	2.3	-
Melrose Road, FI	FL19	*G. radians*	∞	8.0	-
Nelsons Drain	FL20	*C. corioensis*	∞	1.5	-
Nelsons Drain	FL21	*C. corioensis*	4751	1.3	-
Previously undated sites					
Egg Lagoon, KI	K21	*K. scalarina*	1184	0.4	1044-1300
Egg Lagoon, KI	K22	*K. scalarina*	1512	0.4	1313-1760
Egg Lagoon, KI	K19	*K. scalarina*	1789	1.0	1443-2273
Reekara, KI	K17	*K. scalarina*	464	<0.2	312-650

[1]ND, Not determined.

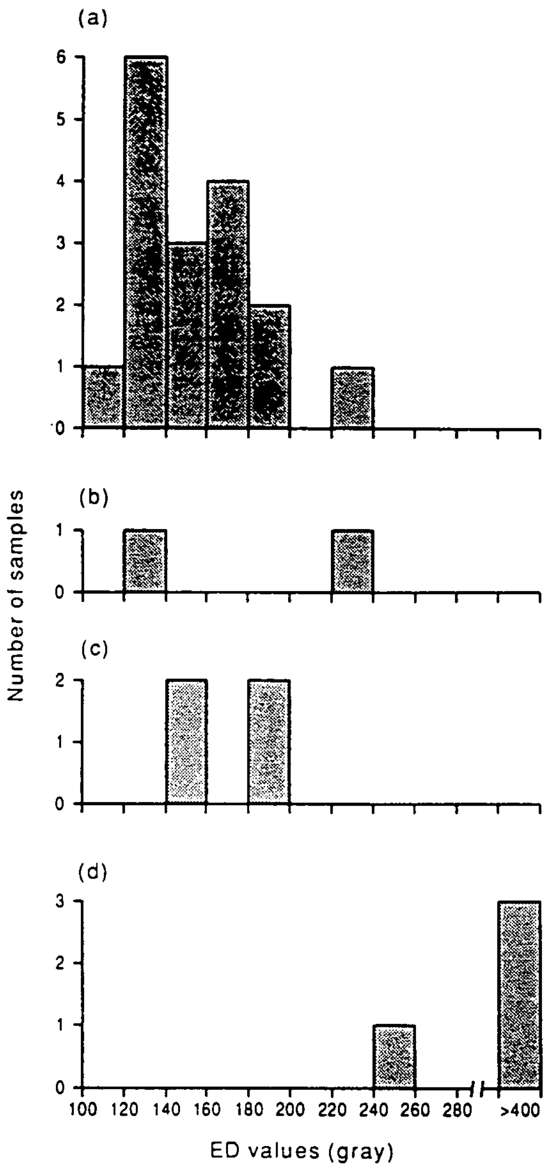

Figure 5 Gamma equivalent dose (ED) values of aragonite shell samples at Australian sites regarded as last interglacial in age. (a) Data from previously studied sites in Western Australia (Hewgill *et al.* 1983) and at Warrnambool, western Victoria (Goede 1989). (b), (c) and (d) Data from three sites in the Bass Strait islands. (b) Yellow Rock River, King Island; (c) North East River Estuary, Flinders Island; and (d) The Patriarchs, Flinders Island. Note the anomalously high values for The Patriarchs site.

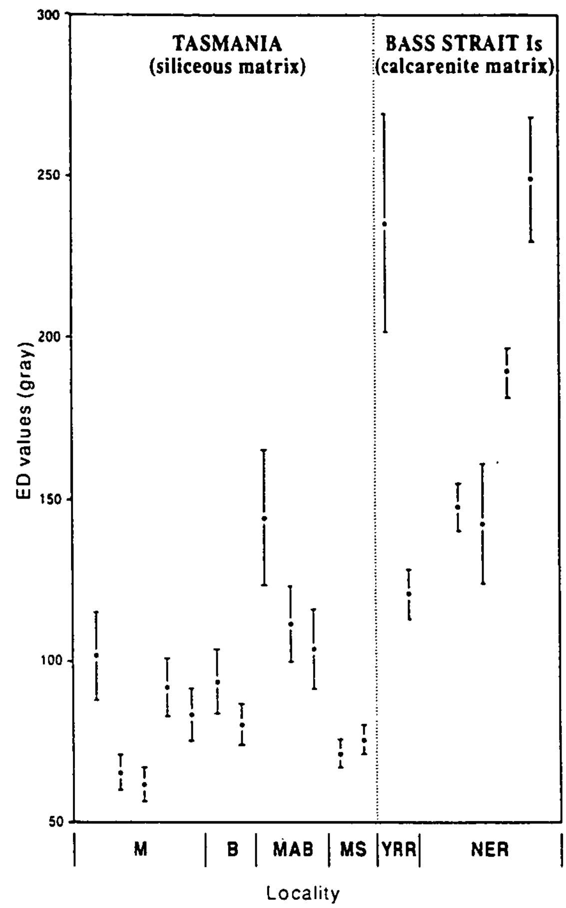

Figure 6 Comparison of gamma equivalent dose (ED) values of shell samples from sites on the Tasmanian mainland and the Bass Strait islands. Last interglacial sites in Tasmania are characterized by a siliceous matrix with a low content of radioactive elements. The Bass Strait islands sites are characterized by a calcareous matrix with a relatively higher content of radioactive elements. The contrast is reflected in the ED values that, for sites of similar age, are significantly lower for Tasmanian mainland sites than for samples from the Bass Strait islands. Sample localities: M, Montagu; B, Broadmeadows; MAB, Mary Ann Bay; MS, Mowbray Swamp; YRR, Yellow Rock River and NER, North East River.

exposed them to a higher dose of cosmic radiation than at any of the other sites. The high ED values may be entirely attributable to a much higher radiation dose than is the case at any of the other sites or alternatively, the greater values may reflect an older age. Further research is required before the electron spin resonance data can be said to support a last interglacial age of the deposit.

DISCUSSION

Dating

With the exception of The Patriarchs deposit, a high level of agreement in the amino acid racemization and electron spin resonance data is noted. Both techniques support the relative ages of all the deposits previously determined on the basis of morphostratigraphy and biostratigraphy. An exception, however, is the Egg Lagoon shell bed on King Island where both amino acid racemization and electron spin resonance suggest an Early Pleistocene rather than Late Pleistocene age (cf. Jennings 1959).

Amino acid racemization and electron spin resonance, in conjunction with indirect evidence from radiocarbon dating, indicate that numerous coastal sequences in Tasmania and the Bass Strait islands are coeval and are of last interglacial age (oxygen isotope substage *5e*). The extent of racemization for a range of amino acids in *Katelysia scalarina* reported by Cann *et al.* (1991) from the last interglacial Woakwine Range Barrier Complex from southern South Australia (current mean annual temperature 14°C), is not significantly different to the interglacial data reported here (Table 2). The last interglacial age of the Woakwine Range is based on uranium-series dating of aragonite mud and molluscs and yielded ages of 100 000 ± 30 000 and 125 000 ± 20 000 a, respectively (Schwebel 1984). More recently, Huntley *et al.* (1993) assigned an age of 122 ka to the substage *5e* component of the Woakwine Range based on thermoluminescence dating. The extent of amino acid racemization in molluscs from the Tasmanian region is also consistent with latitude–temperature gradient models, which predict lower extents of racemization at higher latitudes than for fossils of equivalent age from lower latitudes (Wehmiller *et al.* 1988, 1992; Miller & Brigham-Grette 1989; Murray-Wallace *et al.* 1991). Thus, aminostratigraphy indicates that the Tasmanian deposits correlate with other last interglacial sequences in southern Australia that have also been dated independently by the uranium-series method or correlated with uranium-series disequilibrium dated reference sections (Murray-Wallace & Belperio 1991; Murray-Wallace *et al.* 1991).

A numeric age of 94 200 ± 28 300 a based on the extent of valine racemization was previously reported for the Late Pleistocene coastal sequences in Tasmania (Murray-Wallace & Goede 1991). Although this age assessment may appear to underestimate the last interglacial maximum (substage *5e*), subsequent uranium-series analyses on the calcitic bivalve *Pecten meridionalis* from Mary Ann Bay have obtained results consistent with substage *5e* (K. Lambeck pers. comm. 1991).

In a global context, the amino acid racemization data for the last interglacial molluscs from Tasmania and the Bass Strait islands are in accord with Northern Hemisphere results for sites with similar current mean annual temperatures (Wehmiller *et al.* 1988; Miller & Brigham-Grette 1989; Murray-Wallace *et al.* 1991). These data therefore highlight the potential of applying amino acid racemization as an additional method for Late Quaternary global correlations, and support the veracity of the amino acid racemization data reported here.

Despite variations in dose rates with contrasting environments, the ED values for the fossil molluscs from Tasmania, King Island and Flinders Island, with the exception of The Patriarchs site, are in broad agreement with other last interglacial sequences in southern Australia (Hewgill *et al.* 1983; Goede 1989).

Neotectonics

Interest in the last interglacial maximum (oxygen isotope substage *5e*) in recent years has centred on mapping shoreline deposits of this age to determine the Late Quaternary neotectonic history of continental margins (Preece *et al.* 1990; Murray-Wallace & Belperio 1991; Bryant 1992; Ota *et al.* 1992; 1994). Last interglacial coastal deposits are useful for reconstructing neotectonic histories as they are frequently well-preserved, amenable to dating and provide the basis for confident estimation of palaeo-sea-level. In addition, the time since the last interglacial maximum is sufficient to detect even modest rates of vertical crustal movement.

The sea level record of the last interglacial maximum is complex. Studies from uplifted coastal margins indicate a bipartite high sea-level stand for substage *5e* (Chappell & Veeh 1978; Veeh *et al.* 1979; Sherman *et al.* 1993). Although the suggestion of a compound high sea-level stand for substage *5e* has been contested (Ku *et al.* 1990), the last interglacial maximum has been generally ascribed an age of 125 000 ± 5 000 a based on the uranium-series method (Stearns 1984; Edwards *et al.* 1987). Recent studies have more precisely defined the timing of the last interglacial maximum to between approximately 135–115 ka (Lambeck & Nakada 1992; Chen *et al.* 1991; Zhu *et al.* 1993). Although variations in the elevation of the last interglacial sea surface may have been as great as those of the Holocene, evidence from settings remote from plate boundaries that have not experienced demonstrable tectonic uplift, indicate a sea-level stand between 3 and 9 m above present sea-level (Veeh 1966). Accordingly, Murray-Wallace and Belperio (1991) noted that many workers have invoked a 6 m reference level as a *de facto* global 'eustatic' sea-level datum for the last interglacial maximum. They also noted that for the Australian region, the height of the last interglacial sea surface is consistently below the 6 m level commonly cited in the literature. They found that the most consistent 'eustatic' datum from the Australian region is 2 m above present sea-level from Eyre Peninsula in South Australia. Irrespective of the applicability of this datum to the Tasmanian region, differential shoreline elevation data from the Australian mainland (Murray-Wallace & Belperio 1991) collectively indicate that the last interglacial coastal deposits in Tasmania have been uplifted.

In Tasmania, last interglacial coastal sediments typically exceed 11 m above present sea-level. A beach-ridge plain of inferred last interglacial age has also been identified on Robbins Island, along the northwest Tasmanian coast (van de Geer 1981; Bowden & Colhoun 1984; Figure 1). Here, the landward limit of the sloping plain is some 16 m above present sea-level and is in broad agreement with the elevation of the coastal deposits from northwest Tasmania dated in this study. At Mary Ann Bay, coastal sediments occur up to 24.6 m above present sea-level and represent the highest emergent coastal strata of confirmed last interglacial age on the Australian continent (Murray-Wallace & Belperio 1991). Comparable levels are documented for marine sands at Purdon Bay and Break Yoke Creek in northeast Tasmania (Bowden & Colhoun 1984) but reliable dating is required to confirm their age. At Stumpys Bay, quartzose beach ridges attain a maximum height of 32 m above present sea-level (Bowden & Colhoun 1984), but the last interglacial age assigned to the strata comprising the ridges also requires verification. In contrast, the high elevations reported

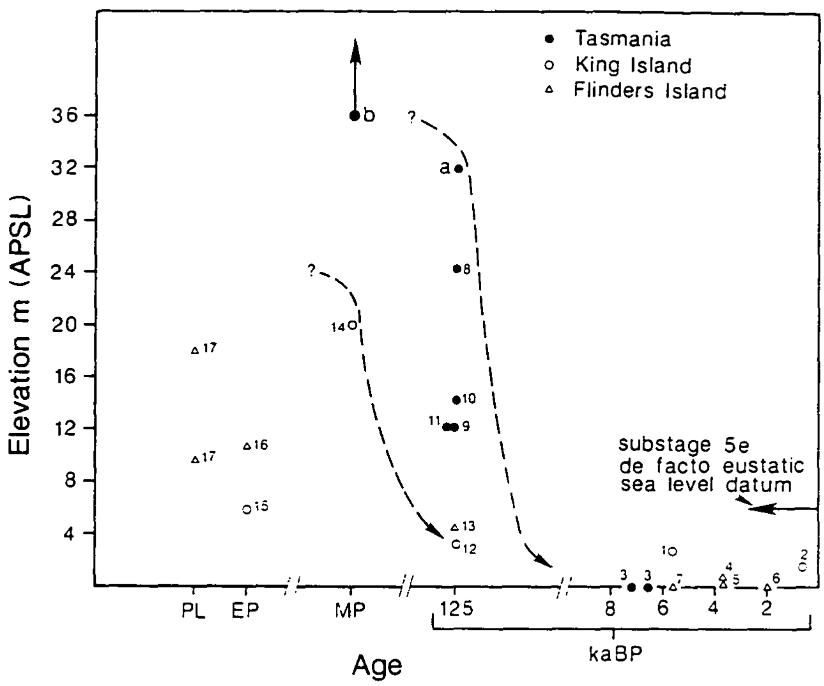

Figure 7 Elevation-time plot of Quaternary coastal strata from Tasmania, King Island and Flinders Island. Localities include: 1, British Admiral Beach and 2, Three Rivers Creek Bay, King Island; 3, Shell Pits Point, Tasmania; 4, Cameron Inlet, 5, Trousers Point, 6, Sandy lagoon, and 7, Fotheringate Bay, Flinders Island; 8, Mary Ann Bay; 9, Montagu, 10, Broadmeadows; 11, Mowbray Swamp, Tasmania; 12, Yellow Rock River, King Island; 13, North East River, Flinders Island; 14, Reekara, and 15, Egg Lagoon, King Island; 16, Memana Formation and 17, Cameron Inlet Formation, Flinders Island. *a*, Stumpys Bay and *b*, Rockbank and Ringarooma deposits of Bowden and Colhoun (1984). PL, Pliocene; EP, Early Pleistocene and MP, Middle Pleistocene. The dashed lines are included to highlight the contrasting trends in elevation for coeval deposits, from different geographic settings. A *de facto* eustatic sea-level datum for the last interglacial maximum of +6 m above present sea-level (APSL) is indicated.

for the last interglacial strata in Tasmania are not evident on King Island or Flinders Island (Figure 7). Here, substage 5*e* coastal sediments identified thus far occur below the widely cited *de facto* global 'eustatic' datum of 6 m above present sea-level.

Examination of the Holocene and earlier Pleistocene records further constrains the nature and timing of neotectonism in this region. Coastal sediments of Early to Middle Pleistocene age on the Bass Strait islands generally occur at a range of elevations up to 20 m above present sea-level. Given that the oxygen isotope record from deep-sea cores (Shackleton & Opdyke 1973) indicates that interglacial sea-level maxima during the Quaternary were comparable to the present, then some tectonic uplift is apparent for King Island and Flinders Island since the early Quaternary. However, this uplift history appears to have terminated before substage 5*e*, as the islands do not provide evidence for uplifted last interglacial strata. The timing of the onset of uplift on mainland Tasmania is not known. Bowden and Colhoun (1984), however, presented evidence for two uplifted coastal deposits of presumed Middle Pleistocene age from northeastern Tasmania. The widespread occurrence of emergent last interglacial coastal strata in Tasmania confirms that uplift has occurred in this region following substage 5*e*. However, with the exception of high-energy shingle-cobble deposits of probable storm origin (e.g. British Admiral Beach and Three Rivers Creek Bay, King Island), there is no evidence for emergent Holocene coastal strata on the Bass Strait islands or in Tasmania. Collectively, these observations suggest a southerly shift in the locus of uplift with time (Figure 7).

Clearly, a mechanism is required to explain these observations. In accounting for the emergent last interglacial strata, Bowden and Colhoun (1984) dismissed glacio-eustatic and hydro-isostatic crustal readjustments in view of the restricted ice cover in Tasmania during the last glaciation and the narrow continental shelf around Tasmania. An uplift model based on either hotspot activity or crustal underplating associated with the northward movement of the Australian Plate has been examined (Bowden & Colhoun 1984; Sutherland *et al.* 1989; Murray-Wallace & Goede 1991). Further detailed geophysical studies are required, however, to test these hypotheses.

Geological maps of the basement rocks, showing their relationship to the Late Pleistocene sequences within the study areas, have not identified regional-scale faults active during the Late Quaternary (Burrett & Martin 1989). An alternative hypothesis for the emergent coastal strata was advanced by Bryant (1992), who suggested that differential uplift associated with continental-scale tilting, due to the northward movement of the Australian Plate and the interaction of its northern margin at an arc-continent collision zone. Although this is apparently supported by trend-surface analyses of differential shoreline elevation data for last interglacial coastal deposits from Australia (Bryant 1992), considerably more research is required to resolve the geophysical basis for the origin of the raised shoreline deposits reported in this study. Understanding the processes responsible for the uplift of the Pleistocene

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coastal sequences in the Tasmanian region represents a major challenge for future studies of the Quaternary coastal stratigraphy of southeastern Australia.

CONCLUSIONS

(1) A generally high level of concordance is noted for the amino acid racemization and electron spin resonance data for molluscs from Quaternary coastal deposits in Tasmania and the Bass Strait islands. The results of these dating methods are also in general accord with previously established biostratigraphic, lithostratigraphic and geomorphologic frameworks for the relative ages of Quaternary coastal strata.

(2) Amino acid racemization and electron spin resonance dating have confirmed the widespread occurrence of last interglacial coastal deposits in Tasmania and the Bass Strait islands. The last interglacial age (oxygen isotope substage 5*e*) assigned to these deposits is supported by aminostratigraphic correlations with uranium-series dated coastal deposits elsewhere in southern Australia.

(3) The coastal strata indicate a spatial and temporal shift in the centre of neotectonic uplift in southeastern Australia during the Quaternary. Early Pleistocene and Middle Pleistocene coastal strata on the Bass Strait islands provide evidence for uplift, but this is not evident in the Late Pleistocene and Holocene records in this region. Although last interglacial strata are emergent on mainland Tasmania, Holocene coastal strata do not indicate neotectonic uplift. On this basis, neotectonic uplift occurred earlier on the Bass Strait islands than in mainland Tasmania, and may relate to the northward movement of the Australian Plate. It is difficult to assess whether these processes continue today in view of the absence of emergent Holocene coastal strata. The geophysical basis for uplift remains unresolved.

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Evidence of Younger Dryas and Neoglacial cooling in a Late Quaternary palaeotemperature record from a speleothem in eastern Victoria, Australia

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ABSTRACT: A calcitic stalagmite collected from a limestone cave in the Buchan area of eastern Victoria has been dated by three mass-spectrometric uranium series analyses. Two growth phases are represented: the older from 13.4 to 10.6 ka and the younger from 3.2 to 2.1 ka. Oxygen isotope analysis reveals that temperatures were below present-day values at all times, but particularly cool conditions are indicated between 12.3 and 11.4 ka, and Neoglacial conditions occurred at about 3 ka. The older cold climate event is clearly synchronous with the Younger Dryas in Europe and this is the first time that strong evidence for this event has been found in Australia. Carbon isotope variations are interpreted as indicating changes in plant productivity on the surface and are most likely controlled by variations in summer rainfall. They indicate particularly high levels of plant productivity from 11.5 to 11.0 ka.

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KEYWORDS: speleothem; stable isotope analysis; uranium series dating; Younger Dryas; Australia.

Introduction

The aim of the study is to examine Late Quaternary variations in oxygen and carbon isotope ratios ($^{18}O/^{16}O$ and $^{13}C/^{12}C$) in a Victorian speleothem and to interpret them in terms of environmental change.

The calcite speleothem examined in this paper was collected from Royal Cave, a high-level cave that forms part of the Dukes Cave System, containing over 5 km of passage and developed in the folded Devonian Buchan Caves Limestone in the Buchan River Valley of Eastern Victoria (148°10′E, 37°30′S) at an altitude of between 60 and 100 m above sea-level (Fig.1). The speleothem was apparently broken during the development of Royal Cave as a tourist cave and its exact provenance is not known.

The speleothem was bisected longitudinally and one half preserved for tourist display. From top and bottom of the other half, samples were taken for alpha particle spectrometry uranium series disequilibrium dating. The remaining portion was 250 mm tall and was sampled at 5 mm intervals using a 2 mm drill for oxygen-18 and carbon-13 isotopic analysis (Fig. 2).

In humid temperate cave environments, calcite deposition usually takes place under conditions of high humidity and near constant temperature, approximately equal to the mean annual temperature at the surface. Exceptions to this are likely to be found only in close proximity to cave entrances. Because temperatures in Royal Cave have been strongly affected by tourist traffic, the air temperatures used for this study were those observed by Canning (1985) in Moons Cave, a former tourist cave in close proximity to Royal Cave. She recorded a mean annual temperature of 15°C, with a temporal variation of 1.3°C. Relative humidity measurements at six stations within the cave showed an average relative humidity of 92–93%.

Geochronology

Age determination of the speleothem (RO) was attempted originally by alpha particle spectrometry of two samples taken from the base and top of the speleothem. Dating was unsuc-

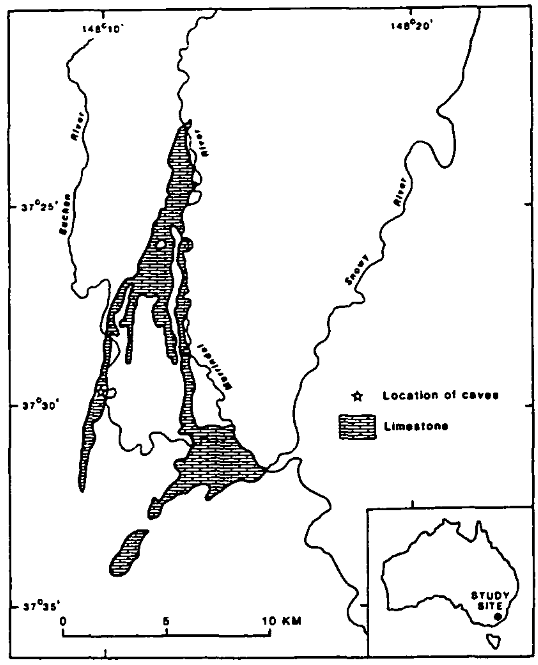

Figure 1 Location map of the study area and the extent of Devonian limestone (after Webb *et al.*, 1992).

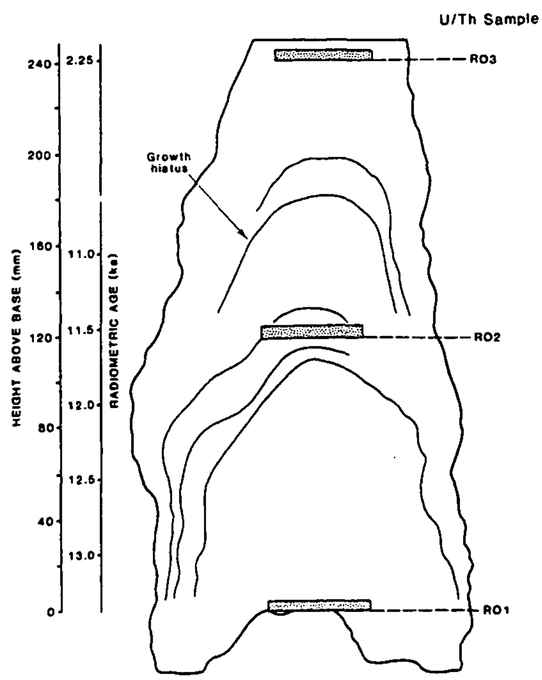

Figure 2 Longitudinal section of RO speleothem showing nature of depositional layering and positions of MS uranium series dates. The time-scale shown is based on these dates.

cessful because of the very low uranium content of between 0.063 and 0.102 μg/g.

Subsequently three samples were taken from the base, middle and top of the speleothem for MS U/Th analysis as shown in Fig. 2. Analytical details of these samples are given in Table 1. The basal and middle samples were analysed twice. The age determinations suggest that the growth hiatus at 180 mm, indicated by an abrupt colour change from milky white to translucent calcite, represents a significant time gap in the depositional record (Fig. 2). A linear growth rate was assumed in order to calculate a time-scale for the lower section of the stalagmite, using sample RO1 together with the average of the two age determinations for RO2. The lower section appears to have been deposited between approximately 13.4 and 10.6 ka indicating a growth rate of some 65 mm ka^{-1}. The upper section is dated by only one analysis (RO3), yielding an age of 2.25 ka at 242.5 mm. On the assumption that the upper section grew at a similar constant rate to the lower section, deposition is found to have occurred from 3.2 to 2.1 ka.

Nature of stable isotopes

The study requires a consideration of the stable isotopes of hydrogen, oxygen and carbon. Isotopic measurements are expressed in per mille (‰) using the delta notation. δD and $\delta^{18}O$ are measured relative to the SMOW (standard mean ocean water) standard where measurements relate to water. $\delta^{18}O$ and $\delta^{13}C$ values relating to calcite are measured relative to the PDB (Peedee Belemnite) standard. The following subscripts are used: p (precipitation), w (seepage water) and c (calcite).

The isotopic composition of precipitation normally tends towards isotopically lighter values with increasing latitude, altitude and continentality (Dansgaard, 1964) and shows significant seasonal fluctuations. Seepage water, collected as roof drips in caves shows little isotopic variation throughout the year, and in southeastern Australia its composition tends to approximate to the weighted mean of the isotopic composition of winter precipitation (Goede and Hitchman, 1984).

Isotopic composition of calcitic speleothems, if deposited under conditions of isotopic equilibrium, is determined by the composition of the seepage water from which the calcite is precipitated together with a temperature dependent fractionation effect. Composition may change over time either because of changes in seepage water composition or because of changing cave temperatures. Cave temperatures show little annual variation and in most caves tend to approximate to the mean annual temperature at the surface. If mean annual surface temperatures change over time in response to a changing climate the cave temperature will adjust accordingly.

In the vast majority of the world's karst areas, the oxygen isotope values of speleothems are negatively correlated with mean annual cave temperature — the temperature effect. The Buchan speleothem clearly fits this pattern (Fig. 4), with $\delta^{18}O$ values apparently less negative at times of cooler temperatures. However, at Mole Creek and in the Florentine Valley of Tasmania (Goede and Hitchman, 1984; Goede *et al.*, 1986, 1990) and at Vancouver Island in western Canada (Gascoyne *et al.*, 1980, 1981) the relationship between $\delta^{18}O$ values of speleothems and temperature is positive. The differences between the Tasmanian sites and Buchan are surprising as they are only 500–600 km apart. There are also significant differences between Victorian and Tasmanian sites in terms of the present-day isotopic composition of vadose dripwaters, which are 1 to 1.5‰ heavier in Tasmania than at Buchan.

The contrast is also shown by the different isotopic compositions of rainfall at Cape Grim, an atmospheric baseline

Table 1 Uranium series MS data and radiometric ages

Sample	^{238}U (μg g^{-1})	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	^{230}Th (pg g^{-1})	$^{230}Th/^{234}U$	Age (yr)
RO1	0.07953 ± 0.00010	1.34131 ± 0.00038	11.25 ± 0.31	0.2017 ± 0.0041	0.1160 ± 0.0023	13,343 + 294-292
RO1 (repeat)	0.07600 ± 0.00010	1.36327 ± 0.00030	Not measured	0.1893 ± 0.0097	0.1121 ± 0.0056	12,863 + 699-694
RO2	0.06308 ± 0.00008	1.3616 ± 0.0019	33.36 ± 0.82	0.1414 ± 0.0032	0.1006 ± 0.0022	11,540 + 293-292
RO2 (repeat)	0.08170 ± 0.00015	1.3253 ± 0.0055	29.11 ± 0.41	0.1768 ± 0.0024	0.1001 ± 0.0013	11,480 + 215-213
RO3	0.03335 ± 0.00010	1.3154 ± 0.0018	4.35 ± 0.051	0.01465 ± 0.00017	0.02041 ± 0.00023	2,253 + 30-30

station in northwestern Tasmania (150–200 km northwest of the Tasmanian cave sites), compared with Melbourne (300 km west of Buchan). These two stations are the closest sites to the Tasmanian cave sites and Buchan, respectively, for which detailed rainfall isotopic data are available. Despite the fact that the Cape Grim station is south of Melbourne and considerably colder (mean annual temperatures of 12.3°C and 15.4°C respectively) it has isotopically heavier rainfall. Arithmetic/weighted means for Cape Grim are −3.8/−4.4‰, compared with −4.6/−5.1‰ for Melbourne (Rozanski *et al.*, 1993).

Cape Grim oxygen isotope data also show a strong seasonal variation with more negative values in the winter months, a typical pattern for the mid-latitudes (Rozanski *et al.*,1993; Desmarchelier, 1994). There is a statistically significant positive correlation between monthly $\delta^{18}O$ values and mean monthly temperatures. In contrast to Cape Grim, the Melbourne data display an anomalous pattern. The $\delta^{18}O$ values are lighter than might be expected for that latitude. They display a poorly defined winter minimum and a pronounced maximum in October–December. There is no significant statistical correlation between monthly values and mean monthly temperatures. The causes of these features are related to the origin of the air masses that precipitate Melbourne's rainfall (Wright, 1988) and will be discussed in more detail elsewhere (Webb, in preparation). Although no isotopic record of precipitation is available for the Buchan area, isotopic data on cave dripwaters, to be presented in this paper, indicate similarities between Melbourne and Buchan.

Interpretation of the carbon isotope variations within speleothems deposited under conditions of isotopic equilibrium have long been a contentious issue. Much relevant research has been done in recent years and three explanations can now be advanced to account for changes within a single speleothem.

1. Changes in the relative abundance of two groups of plants that follow different photosynthetic pathways: C3 and C4 (Brooke *et al.*, 1990; Dorale *et al.*, 1992; Talma and Vogel, 1992). Because C4 plants are predominantly tropical grasses (Teeri and Stowe, 1976; Tieszen *et al.*, 1979) this explanation is not relevant to the Buchan area.
2. Changes in vegetation productivity, which control the amount of isotopically light organic matter supplied to the soil, which is broken down to provide CO_2 to the soil atmosphere, where it mixes with CO_2 derived directly from the atmosphere. Isotopic variations in soil carbonates (Quade *et al.*, 1989) and subaqueous wallcrust in a karst spring (Coplen *et al.*, 1994) have also been attributed to this cause.
3. Changes in the isotopic composition of carbon in atmospheric CO_2, with glacial periods being characterised by less negative values. The most reliable estimate so far suggests a change of 0.7‰ (Marino *et al.*, 1992). If this estimate is confirmed, the effect of changes in the isotopic composition of atmospheric CO_2 on that of the soil is likely to be quite small. More significant are changes due to the burning of fossil fuels, estimated at −2.2‰ since 1900 (Baskaran and Krishnamurthy, 1993), and instrumental records show a change of −0.23‰ from 1982 to 1993 (Francey *et al.*, 1995).

Isotopic sampling

Before palaeotemperature work could be done on any speleothems from the Buchan Caves area it was necessary to sample modern seepage waters and actively growing straw stalactite tips in order to determine the isotopic composition of both. As Royal Cave is an active tourist cave it was not feasible to collect samples there, so they were collected in nearby Moons Cave.

Water sampling

It was feasible to visit the area only once, in January 1992, to collect samples. Bottles to collect drip water had been set up a fortnight earlier to ensure representative samples for analysis. This was regarded as adequate because it has been shown elsewhere that there is little seasonal variation in the composition of dripwaters in humid temperate environments (Goede *et al.*, 1982; Yonge *et al.*, 1985). Five water samples were collected.

Sampling of modern calcite

In order to estimate the oxygen and carbon isotope composition of modern calcium carbonate being deposited under conditions of oxygen isotope equilbrium, actively growing straw stalactite tips were collected from the same area of the cave as the drip waters. Because of the rapid growth rate of straw stalactites the assumption can be made that the material has been deposited during the last few years (Harmon *et al.*, 1978).

Speleothem sampling

The speleothem (RO) had been cut in two along its length to provide a longitudinal section, as shown in Figure 2.

To determine whether deposition of the stalagmite had taken place under conditions of oxygen isotope equilibrium, three sets of eight 2-mm-diameter samples for isotopic analysis were drilled from each of three growth layers.

Samples for isotopic analysis were also obtained by drilling along the core at 5 mm intervals using a 2 mm drill. This provided a set of 49 samples that could be used to construct a dated longitudinal profile of secular change in the values of $\delta^{18}O_c$ and $\delta^{13}C_c$.

Isotopic analysis

Water samples

Water samples were analysed to determine both deuterium–hydrogen and oxygen isotope ratios. Samples for δD_w analysis were prepared by converting water to hydrogen by reaction with zinc shot at 450°C, using the technique as modified by Kendall and Coplen (1985). Gas samples were then measured on a VG Micromass 602D mass spectrometer with an analytical precision of 2 per mille. For $\delta^{18}O_w$ determination water samples were equilibrated with CO_2 gas at 25°C for 5 h in a VG Isoprep 18. The gas samples were then dried and analysed on a VG SIRA Series II mass spectrometer with an analytical precision of 0.05 per mille. The results of both sets of analyses are shown in Table 2.

As can be seen from Table 2, δD_w values range from −40 to −45‰, with an average value of −43‰, and $\delta^{18}O_w$ values range from −6.20 to −6.74‰, with an average value of −6.44‰. The general relationship between δD and $\delta^{18}O$ values is well known. According to Dansgaard (1964) the so-called meteoric water line is best expressed as

$$\delta D = 8\delta^{18}O + 10‰ \tag{1}$$

Substituting the average value of $\delta^{18}O_w$ (−6.44‰) in this expression yields a δD_w value of −41.5‰, which falls well within the range of measured values.

When these isotopic values are compared with the oxygen isotope record of Melbourne precipitation, we find that the values fall within the lower part of the range for monthly means during the winter months. When compared with the 10 yr (1982–1991) record at the Cape Grim baseline station, which has a similar altitude to the Buchan site, it is clear that the Buchan waters are much lighter isotopically despite the lower latitude. Isotopic values at two inland Tasmanian karst sites (Mole Creek and the Florentine Valley) are also significantly heavier despite their higher latitude and elevation (Goede *et al.*, 1986–1990). The reasons for these differences will be explored in detail elsewhere (Webb, in preparation).

Modern calcite

For isotopic analysis of all calcite samples, CO_2 was prepared by reacting samples in a vacuum with anhydrous H_3PO_4. Both $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios were determined as ‰ PDB using a VG SIRA Series II mass spectrometer with an average measurement precision of approximately 0.01‰. The oxygen-18 and carbon-13 values of nine modern calcite samples determined are shown in Table 3.

Table 2 Deuterium–hydrogen and oxygen-18 determinations of five dripwater samples from Moons cave Buchan area

Sample	δD_w (‰ SMOW)	$\delta^{18}O_w$ (‰ SMOW)
MN1	−44	−6.45
MN2	−43	−6.47
MN3	−40	−6.32
MN4	−45	−6.74
MN5	−42	−6.20
Average values	−43	−6.44

Correlation of the two data sets gives $r = 0.836$, a clear indication that some of the samples have been fractionated. The two samples least likely to have been affected are MS4 and MS5 because they have the lightest values for both isotopes. Oxygen isotope equilibrium deposition in Moons Cave under present-day conditions can be estimated by a $\delta^{18}O_c$ value of approximately −5.8‰ PDB, corresponding to a $\delta^{13}C_c$ value of approximately −9.6‰ PDB.

Cave temperature calculation

In order to see if the estimates for $\delta^{18}O_w$ for cave dripwaters and the $\delta^{18}O_c$ of modern calcites are approximately correct, an independent estimate of present-day cave temperature can be made using these values by applying the expression of Craig (1965)

$$t = 16.9 - 4.2(\delta_c - \delta_w) + 0.13(\delta_c - \delta_w)^2 \tag{2}$$

This requires the conversion of $\delta^{18}O_w$ values to the PDB standard by adding 0.22‰ (Craig, 1961).

Using the mean value of dripwater, −6.44‰, SMOW (−6.22‰ PDB) and a value of −5.80‰ PDB for modern calcite and substituting these in expression (2) we obtain $t = 15.16$°C. This value is well within the range of temperatures actually measured in Moons Cave by Canning (1985).

Speleothem calcite

Analyses of the three sets of eight growth layer samples are presented in Fig. 3. In all three sets there is an absence of correlation at the 5% level of significance between the pairs $\delta^{18}O_c/\delta^{13}C_c$, $\delta^{18}O_c/D$ and $\delta^{13}C_c/D$, where D is the distance along the growth line from the centre of the stalagmite core. It indicates that the speleothem has been deposited under conditions of isotopic equilibrium. Another test of such equilibrium is made by correlating the $\delta^{18}O_c$ and $\delta^{13}C_c$ values of the 49 samples taken along the length of the core. Correlation analysis yields $r^2 = 0.181$. The lack of strong correlation provides further evidence of isotopic equilibrium deposition.

The results of stable isotope analysis of samples taken along the length of the core are provided in Fig. 4, where five-point

Table 3 Oxygen-18 and carbon-13 values determined for nine straw stalactite tips from Moons Cave, Buchan area

Sample	$\delta^{18}O_c$ (‰ PDB)	$\delta^{13}C_c$ (‰ PDB)
MS1	−5.74	−9.31
MS2	−5.59	−7.50
MS3	−5.76	−8.86
MS4	−5.85	−9.53
MS5	−5.82	−9.61
MS6	−5.68	−8.26
MS7	−5.55	−8.42
MS8	−5.35	−7.03
MS9	−5.62	−9.40

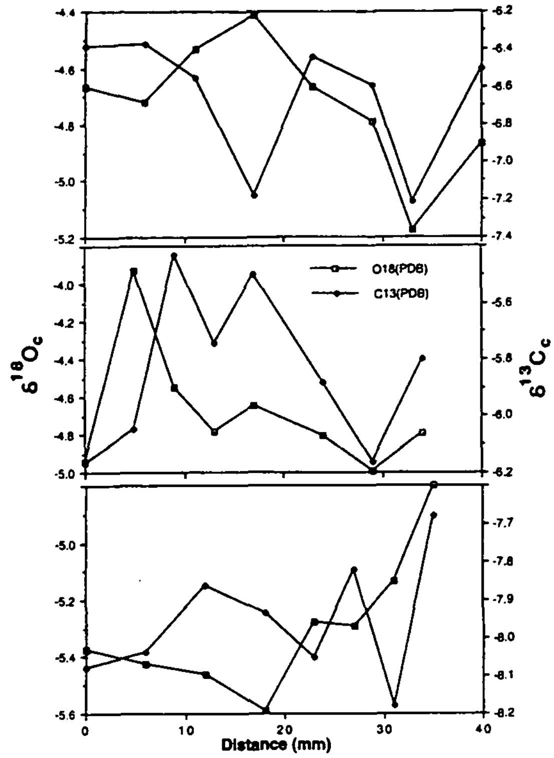

Figure 3 Patterns of $\delta^{18}O_c$ and $\delta^{13}C_c$ values with distance from the centre along each of three growth layers to test for deposition under conditions of isotopic equilibrium.

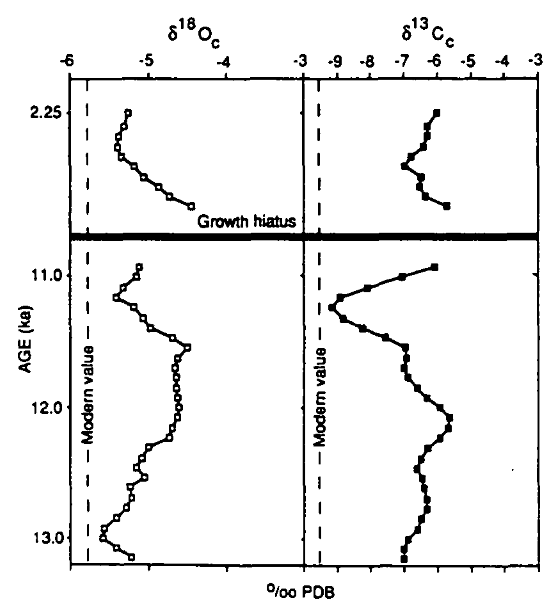

Figure 4 Five-point running means of temporal variations in the values of $\delta^{18}O_c$ and $\delta^{13}C_c$ measured at 5-mm intervals along the longitudinal axis of the stalagmite (RO) from Royal Cave, Buchan. The modern values shown on the diagram have been determined from straw stalactite tips at nearby Moons Cave. The $\delta^{18}O_c$ values bear a negative relationship to mean annual temperature.

smoothed values are plotted against estimated age on the assumption of a uniform growth rate. The $\delta^{18}O$ values are consistently heavier isotopically than the modern value of −5.8‰. Because world temperatures are known to have been lower than today during much of the time span covered by the stalagmite, it confirms a negative relationship between $\delta^{18}O$ values and mean annual temperature. This is the relationship found in most of the world's stalagmites examined so far but is opposite to that found in the nearby island of Tasmania (Goede *et al.*, 1986, 1990).

Temperatures thus appear to have been lower than today throughout the two growth periods represented in the depositional record, although it is not possible to make a precise estimate of how much lower they may have been.

Two particularly cool periods are indicated. The older one from 12.3 to 11.4 ka clearly corresponds to the Younger Dryas stadial in Europe. The younger cold climate event is indicated at about 3 ka and coincides with the resumption of speleothem deposition following a major growth hiatus between 10.7 and 3.0 ka.

Running mean isotopic values for $\delta^{13}C_c$ vary from approximately −5.8 to −9.2‰. As discussed earlier, likely causes have been suggested to account for temporal carbon isotope variations in a single speleothem but only two are relevant to the Buchan area.

The atmospheric explanation is unlikely to account for any changes in isotopic values in excess of 1 per mille nor is it capable of explaining the rapid variations that occurred between 11.5 and 11.0 ka. The changes observed are believed to reflect predominantly changes in vegetation productivity, which in turn are likely to be related to changes in moisture availability during the growing season.

Discussion

Many speleothems from caves in southeastern Australia, including the Buchan area, are characterised by low uranium contents and this makes them difficult to date with any degree of precision by uranium series disequilibrium techniques using conventional alpha spectrometry. The introduction of thermal ionisation mass spectrometry (TIMS) has enabled precise dating of such speleothems. High precision dating makes it possible to compare isotopic records of speleothems with well-dated climatic proxy records from elsewhere in the world.

In the RO stalagmite from Buchan, the period of time between 12.3 and 11.4 ka characterised by high values of $\delta^{18}O_c$ can be correlated confidently with a cold climate event (Younger Dryas) between 12.9 and 11.7 ka in the very precisely dated ice-core record (GISP 2) from Greenland (Taylor *et al.*, 1993). The Younger Dryas event was identified originally in pollen sequences from western Europe, and its age was determined by radiocarbon dating. These ages are now known to be underestimates (Bard *et al.*, 1990). The time discrepancies in the boundary values between the ice-core and speleothem records are within the limits of accuracy of the U-Th MS dates. This is further confirmation of the negative relationship between the oxygen isotope ratio of speleothems and mean annual temperature at Buchan. Until 1994 most evidence for the Younger Dryas event in the Southern Hemisphere has come from pollen profiles in South America and interpretation of the evidence has been a source of considerable debate (Heusser, 1993; Markgraf, 1993). Denton and Hendy (1994) have now presented conclusive evidence that the Waiho Loop terminal moraine related to an advance of the Franz Josef Glacier on the western flank of the Southern Alps in New Zealand is synchronous with the Younger Dryas in the North Atlantic region.

A Holocene cold climate event is indicated at about 3 ka at the resumption of growth of the speleothem following a major depositional hiatus. This is in good agreement with evidence from two stalagmites from different karst regions in Tasmania with records indicating lower mean annual temperatures (2°–3°C) between 4 and 3 ka (Goede and Hitchman, 1984; Goede *et al.*, 1990). It also confirms evidence from the Snowy Mountains in southern New South Wales by Costin (1972), who presented ^{14}C dated evidence for increased periglacial activity and identified a cold phase from 3000 to 1500 radiocarbon years BP. Williams (1978) has summarised evidence of environmental change from the Southern Tablelands of New South Wales. He found that hillslopes were unstable and streams were aggrading between 4000 and 1500 radiocarbon years BP. He suggested lower temperatures, drier and windier conditions and changes in rainfall seasonality as possible causes.

Although temperature differences cannot be quantified, it is possible to calculate a minimum amount of temperature lowering from the RO oxygen isotope record using formula (2). As stated earlier the speleothem oxygen isotope record is affected by two opposing influences. If the cave temperature, which is assumed to be equal to the mean annual temperature at the surface, drops in response to climatic cooling then the oxygen isotope value of any calcite being deposited tends to become isotopically heavier—the temperature effect. This clearly is the dominant factor at Buchan.

This effect may be counteracted to some extent by changes in the isotopic composition of precipitation, which are controlled by the temperature conditions in the moisture source area and in the local atmosphere where moisture is condensing—the precipitation effect. Precipitation will, therefore, tend to become isotopically lighter as the climate cools and this will produce isotopically lighter seepage waters.

However, if we make the assumption that there was no precipitation effect we can use equation (2) to calculate a theoretical mean annual temperature of 12.9°C for conditions of maximum cold during the two cold periods. This provides a minimum estimate for the amount of temperature lowering of 2.25°C relative to the present.

The time sequence of $\delta^{13}C_c$ values in Fig. 4 is believed to represent a record of varying conditions of moisture availability with more negative values indicating more available moisture during the growth period. The values cannot be compared directly with the modern value of −9.6% obtained from straw stalactite tips in Moons Cave. The reasons are firstly that Moons Cave is some distance away from Royal Cave where the RO speleothem was collected and secondly that burning of fossil fuels has significantly changed the $\delta^{13}C$ value of atmospheric CO_2 in recent decades (Baskaran and Krishnamurthy, 1993).

Conclusions

The stalagmite provides a detailed environmental record of two time periods—the older from 13.4 to 10.6 ka and the younger from 3.2 to 2.1 ka. Oxygen isotope values reveal cooler conditions than today, with a stadial between 12.3 and 11.4 ka, contemporaneous with the Younger Dryas in Europe and a glacial advance in the Southern Alps of New Zealand. Neoglacial conditions occurred at approximately 3 ka, followed by a gradual warming. There is considerable evidence for colder conditions at this time from both Tasmania and southeastern Australia.

Temperatures during both cold climate events were at least 2.25°C lower than at present and the temperature drop may well have been greater. It is evident that the Younger Dryas in the Southern Hemisphere was nowhere near as severe as it was in Europe. This supports the notion that the factors leading to its occurrence originated in the northern Atlantic. The large extent of the Southern Ocean is likely to have been responsible for reducing the amplitude of temperature variations quite significantly.

Three hypotheses have been proposed to account for secular variations in speleothem carbon isotope values and they have been examined in the light of the evidence available. It is concluded that at Buchan these changes can be interpreted predominantly in terms of variations in moisture availability during the growing season. Isotopic changes in atmospheric CO_2 may have made a minor contribution.

The speleothem data offer a challenge to palynologists to find evidence from high-resolution pollen cores in order to document the impact on the Australian vegetation cover.

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Significance of strontium and strontium isotope variations in a Tasmanian speleothem

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Abstract

Strontium isotopic and elemental abundances together with oxygen isotopic compositions are reported for a speleothem from south-central Tasmania. Secular variations are present in the strontium content which exhibits a striking bimodal distribution pattern with abrupt changes between two modal groups. Strontium isotope compositions in the speleothem range from 0.70865 to 0.70898, indicating derivation of Sr from at least two distinct sources, the first a persistent one from the overlying limestone, the second a higher $^{87}Sr/^{86}Sr$ component, probably representing input from terrestrial dust. The speleothem record is unusual because it indicates a greater input of more radiogenic Sr dust flux during interstadial times than under full-glacial conditions. If an aeolian origin of some of the strontium contained in speleothems at other inland cave sites around the world can be confirmed, variations in strontium isotope composition will provide high-resolution records of how terrestrial dust flux has varied during the Quaternary. In near-coastal sites significant amounts of strontium may be derived from seasalt and in those areas temporal variation of the element in speleothems may reflect, at least in part, changing distance from the coast due to changes in sealevel.

Keywords: speleothem, strontium, strontium isotope analysis, uranium series dating, Quaternary studies, Tasmania.

1. Introduction

Speleothems grow by precipitation of calcite from a relatively steady supply of cave drip water and as a result preserve a record of the changes in chemistry of the cave water. Strontium isotope compositions also preserve a direct record of the $^{87}Sr/^{86}Sr$ composition of the cave water, for unlike oxygen isotopes, there is no isotopic fractionation of Sr during calcite formation. In south-central Tasmania, the caves have formed in folded Ordovician limestones that at the cave site are not overlain by younger rocks. Hence the surrounding country rocks have a reasonably constant Sr isotopic composition, representative of the Ordovician seawater from which they formed. Variations in the Sr isotopic composition of a speleothem would therefore imply mixing between Sr from the country rock and from one or more additional components such as aeolian dust.

Strontium isotope measurements can be used most effectively where strontium is derived from two sources, each having a distinct and uniform isotopic composition (Faure, 1986, Graustein, 1989). Examples of such mixing may be found in a variety of situations:

(1) In river basins dominated by outcrops of two rock types with markedly different isotopic ratios. Fisher and Stueber (1976) have demonstrated this effect for the Susquehanna River and its tributaries in the eastern United States.

(2) In soils where strontium derived from weathering bedrock may be mixed with strontium derived from aerosols of either marine or continental origin and deposited either as rainout or fallout. Graustein (1989) and Quade *et al.* (1995) have both demonstrated that such effects can be detected over very considerable distances from the source area. Graustein (1989) reports a study of the Tesuque watersheds in the Santa Fe Range of New Mexico where an assessment was made of the contribution of atmospheric strontium relative to a component derived

from chemical weathering of the granitic rocks that underlie the catchments. They found that up to 80 % of the strontium contained in the biomass was derived from atmospherically transported dust while only 20 % was derived from the bedrock. Soil solutions were also shown to be strongly influenced by the atmospheric source. Quade *et al.* (1995) used both strontium and carbon isotope ratios as tracers to determine the origin of soil carbonates in South Australia and western Victoria. In Eyre Peninsula they found that the effects of marine derived strontium could be detected up to several hundred kilometres inland.

For example, dust derived from ancient continental rocks versus young volcanic areas have distinctive compositions reflecting the long-term Rb/Sr and hence different Sr isotopic evolutions of each parent material. Ancient high Rb/Sr continental materials generally have higher $^{87}Sr/^{86}Sr$ ratios whereas more primitive low Rb/Sr basalts have lower ratios. On this basis the strontium isotope composition of dust in the area of deposition can be used to infer possible source areas.

(3) In ice cores where Grousset et al. (1992) used both strontium and neodymium stable isotope ratios to identify the source of continental dust contained in the Antarctic Dome C ice core at the time of the Last Glacial Maximum. They were able to define a predominantly Patagonian provenance for the dust content.

A search has yielded only two previous studies that have examined the Sr isotope composition of speleothems. Nakano *et al.* (1993) have analysed a stalactite in Gyokusendo Cave on Okinawa. They found $^{87}Sr/^{86}Sr$ ratios in the stalactite to be consistently higher than in the limestone and ratios in the groundwater significantly higher than both. They estimated an input of some 10 % of non-limestone strontium believed to have been derived by groundwater circulation from older rocks in the vicinity.

Banner *et al.* (1996) have examined the strontium isotope content in several speleothems from Harrisons Cave on the island of Barbados. They have documented a pattern of changing $^{87}Sr/^{86}Sr$ ratios over the last six thousand years and consider several possible mechanisms that are believed to be influenced by climatic change.

In this study $^{87}Sr/^{86}Sr$ ratios will be used to examine not only the mixing effect of strontium derived from the local limestone with that derived from an aerosol component but also to identify the likely provenance of the aerosol component.

The speleothem under discussion is a 907 mm tall columnar stalagmite (code: FT) from Frankcombe Cave in the Florentine Valley of south-central Tasmania (Figure 1). A full description of the site and its physical environment can be found in Goede, Veeh and Ayliffe (1990) and Goede (1994). The cave occurs in a low hill rising from the floor of the valley at an elevation of 360 m a.s.l. and has been developed in the Middle Ordovician Cashions Creek Limestone of tropical origin exposed in the floor of the valley. The limestone at the site is not overlain by younger rocks that may elsewhere contribute to the strontium content of the seepage waters. There is a thin, discontinuous soil cover rich in organic matter but whose mineral component has been derived from the underlying limestone. The area has not been glaciated during the Quaternary. The cave has a mean annual temperature of 8.3° C (Goede et al. 1982). The climate is a humid temperate one with an annual precipitation of some 1500 mm distributed throughout the year. The natural vegetation consists of wet sclerophyll forest.

The stalagmite was sectioned longitudinally to expose the stratigraphy (Figure 2). Analytical studies were confined to the basal 860 mm which appears to represent continuous deposition. A half core was cut into 5 mm slices which were crushed and homogenised prior to analysis. The sequence provided 170 data points covering a time period originally believed to range from 98 to 55 ka based on three alpha spectrometry uranium series dates.

A continuous record of stable isotope ($\delta^{18}O$ and $\delta^{13}C$) and minor element (Sr and Mg) variation was presented by Goede (1994). The author observed that strontium concentrations showed a bimodal distribution indicating control by a rapidly acting switching mechanism tentatively attributed to the changing direction of strong winds supplying calcitic dust to the ground surface above the

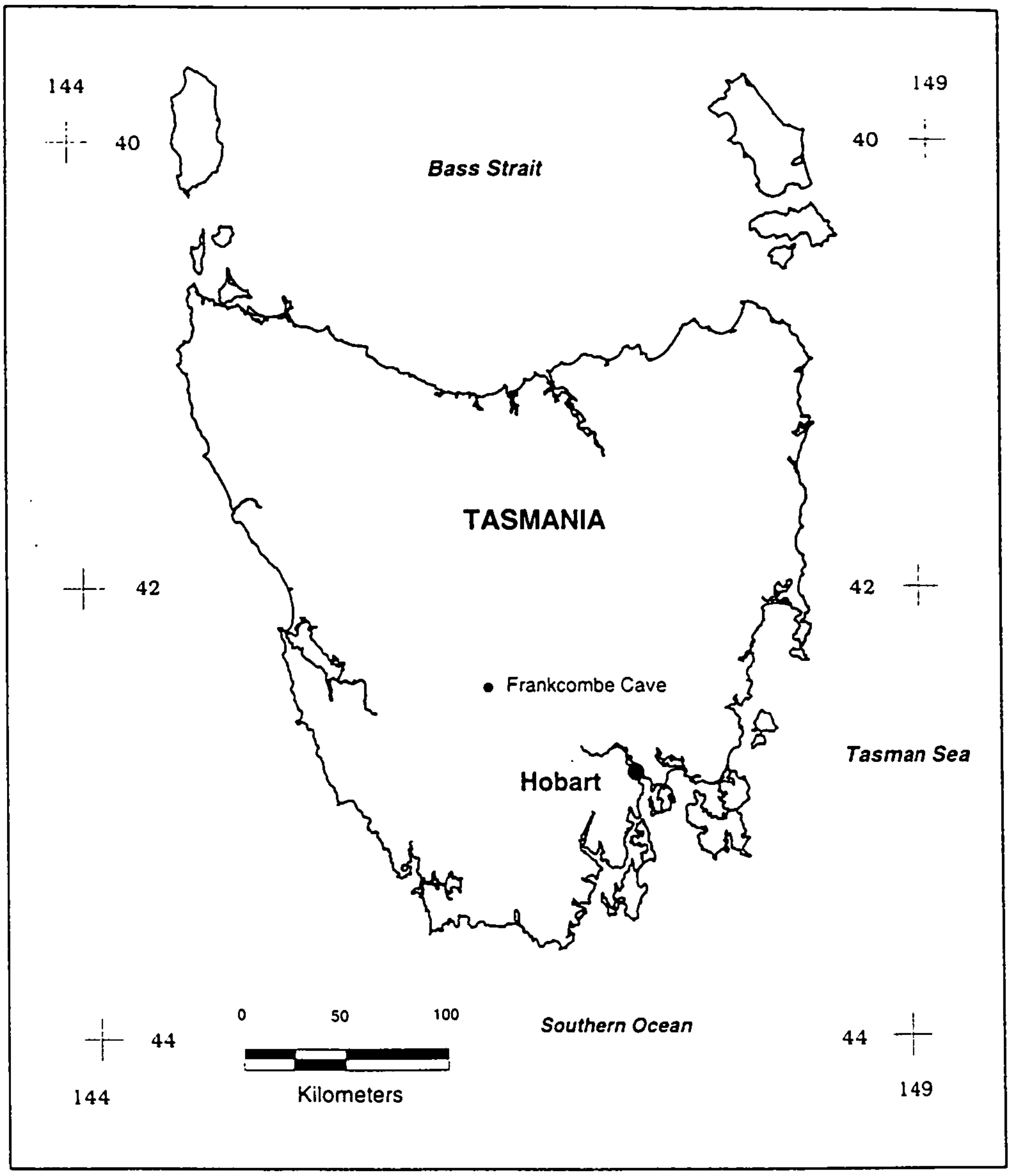

Figure 1 - Locality map showing location of cave site within Tasmania.

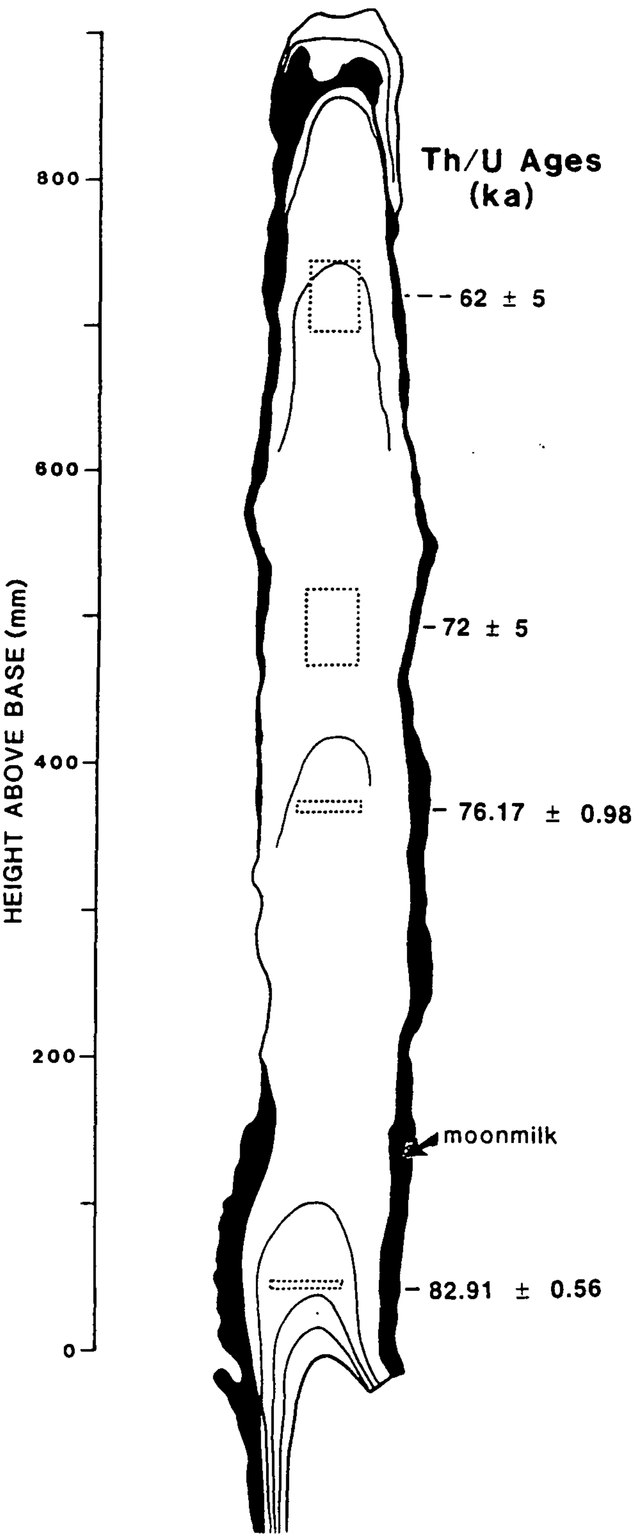

Figure 2 - Longitudinal section of FT stalagmite indicating core stratigraphy and positions and values of relevant uranium series dates.

cave site. However, at the time he was unable to confirm this. The nature of the changes suggests that strontium held by the vegetation and in the soil above the site has only a short residence time.

2. Analytical methods

Samples for oxygen isotope analysis were reacted in vacuum with anhydrous H_3PO_4 followed by purification in a glass extraction line. Values were determined as ‰ relative to the PDB standard using a VG SIRA Series II mass spectrometer with an average measurement precision of approximately 0.01 ‰. The resulting time series is shown in Figure 3.

Tasmanian speleothems, in common with similar material from several other temperate maritime west coast climates, show a positive relationship between $\delta^{18}O$ values of calcite and palaeotemperature (Goede et al. 1986, 1990).

The reason is that glacial-interglacial changes in oxygen isotope ratios appear to be dominated by changes in the isotopic composition of precipitation caused by major temperature and humidity changes at the sites of evaporation. It is attributed predominantly to a major latitudinal shift in the geographical location of moisture source areas. Strong meridional (north-westerly) airflow is believed to have brought moisture from tropical oceanic source areas during interglacial times as it does today. During glacial times strong latitudinal (westerly) airflow is believed to have brought moisture from a temperate oceanic source.

Modern $\delta^{18}O$ values of calcite are estimated at -4.0 ‰ vs PDB (Goede et al., 1986, 1990) and correspond to a mean annual temperature of 8.3° C. Using a formula first proposed by Gascoyne et al. (1980, 1981) it was found that $\Delta\delta^{18}O$ = -0.26 ‰ for every 1 °C lowering of temperature. The procedure for estimating this value is discussed in full detail in Desmarchelier and Goede (1996). The resultant temperature curve is shown in Figure 7.

Strontium analyses were done by atomic absorption spectrometry (AAS) with

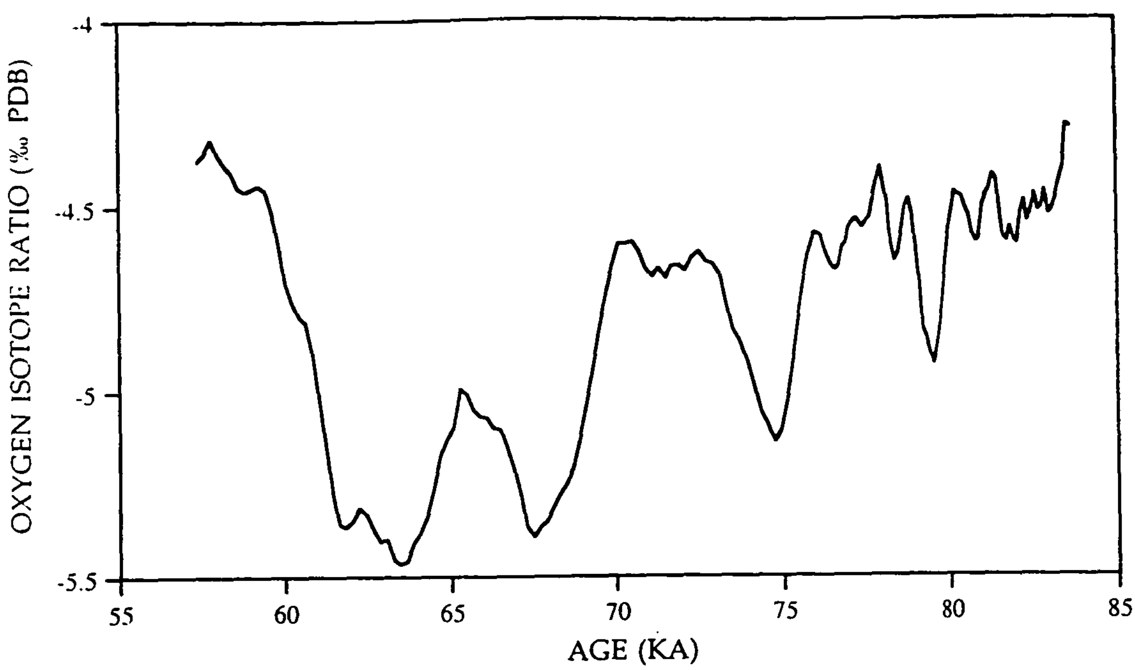

Figure 3 - Five-point running means of temporal variations in $d^{18}O$ values determined for 5 mm intervals along the longitudinal axis of the stalagmite (after Goede, 1994).

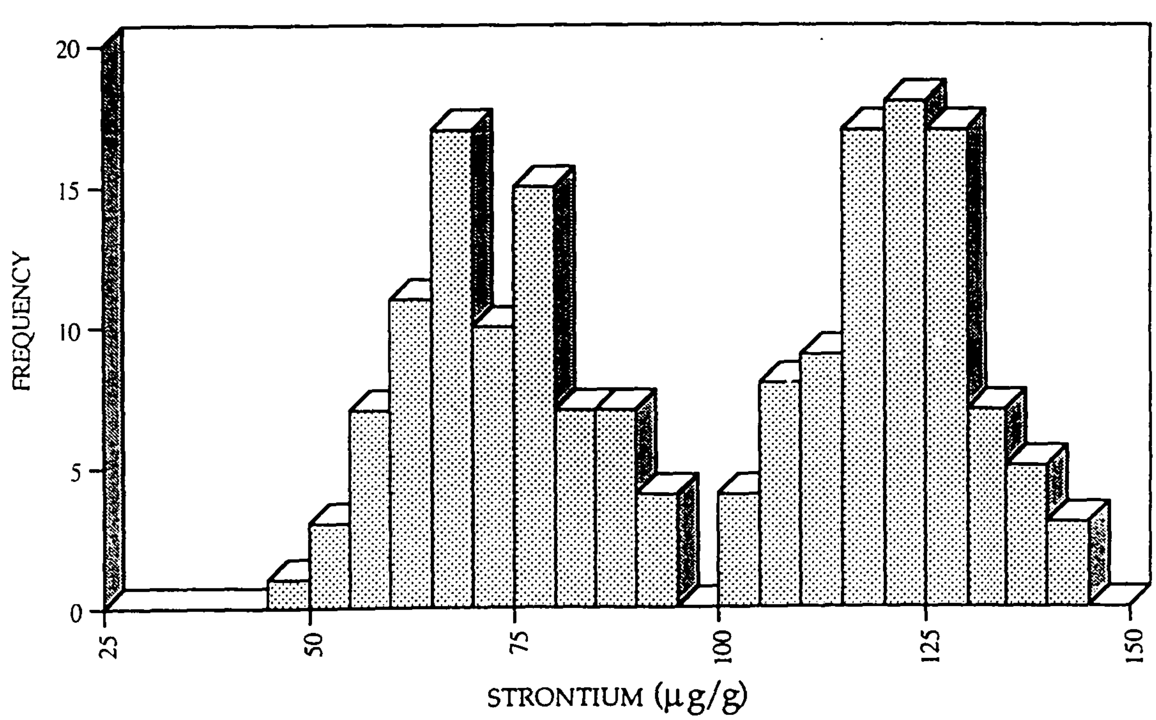

Figure 4 - Histogram showing bimodal distribution of strontium concentrations in 170 samples each representing a 5 mm slice of the core of the FT stalagmite.

a measurement precision of approximately 2% and were found to range from 45 to 144 µg/g but showing a striking bimodal distribution (Figure 4). The profile is shown in Figure 5. Goede (1994) tentatively suggested that the higher mode (100 to 144 µg/g) was due to strontium being added intermittently to the surface above the cave site as a component of aeolian continental dust carried into the region under interstadial conditions from the Australian mainland by strong north-westerly winds, while during glacial conditions strong zonal circulation dominated by westerly winds would cut off the sediment supply.

For the purpose of strontium isotope analysis ($^{87}Sr/^{86}Sr$) ten speleothem carbonate and two limestone samples were crushed in a swing mill and 500 mg samples used for analysis. To analyse for strontium, 50-100 mg was dissolved in dilute HCl and Sr separated from Ca using a large (5 ml) exchange column. Samples were further purified using a second small (1 ml) cation column. After chemical separation samples were evaporated to dryness and then loaded onto single Ta filaments. Strontium isotope compositions were determined on a Finnigan MAT 261 solid-source mass spectrometer using procedures described by McCulloch et al. (1989). Ratios are normalised to $^{87}Sr/^{86}Sr$ = 0.1194 to correct for mass fractionation. For comparison, the value of modern seawater determined in this laboratory is 0.70913 and the NBS 987 standard has a measured value of 0.71021. Strontium concentrations were determined on the same solutions by inductively coupled plasma (ICP) spectrometry.

3. Dating

In two earlier papers (Goede et al. 1990, Goede, 1994) the age range of the stalagmite was estimated between 98 and 55 ka. This was based on three alpha spectrometry dates with the oldest date (FT1) having a particularly large standard error (± 8 ka). This date has been replaced with two much more precise uranium series MS dates (Figure 2). Analytical data and radiometric ages for the four samples relevant to age determination of the stalagmite are shown in Table 1. Age determination of the lower 370 mm of the speleothem is based on interpolation and extrapolation of the FT4 and FT5 ages and yields a mean growth rate of ~48 mm/ka from 84 to 76.2 ka. For the upper part of the stalagmite, age estimation is

Table 1 - Uranium series alpha spectrometry and MS data with radiometric ages. Data for samples FT2 and FT3 are taken from Goede *et al.* (1990).

Sample	U (pg/g)	$^{234}U/^{238}U$	^{230}Th (pg/g)	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	Age (ka)	Height (mm)
FT3	26	1.23 ± 0.04		76	0.44 ± 0.02	62 ± 5	724
FT2	38	1.21 ± 0.03		>1000	0.49 ± 0.02	72 ± 5	496
FT5	47.43 ± 0.04	1.2774 ± 0.0036	0.5084 ± 0.0045	411	0.5147 ± 0.0047	76.17 ± 0.98	372.5
FT4	91.79 ± 0.13	1.2126 ± 0.0006	0.9865 ± 0.0046	179	0.5437 ± 0.0025	82.91 ± 0.56	47.5

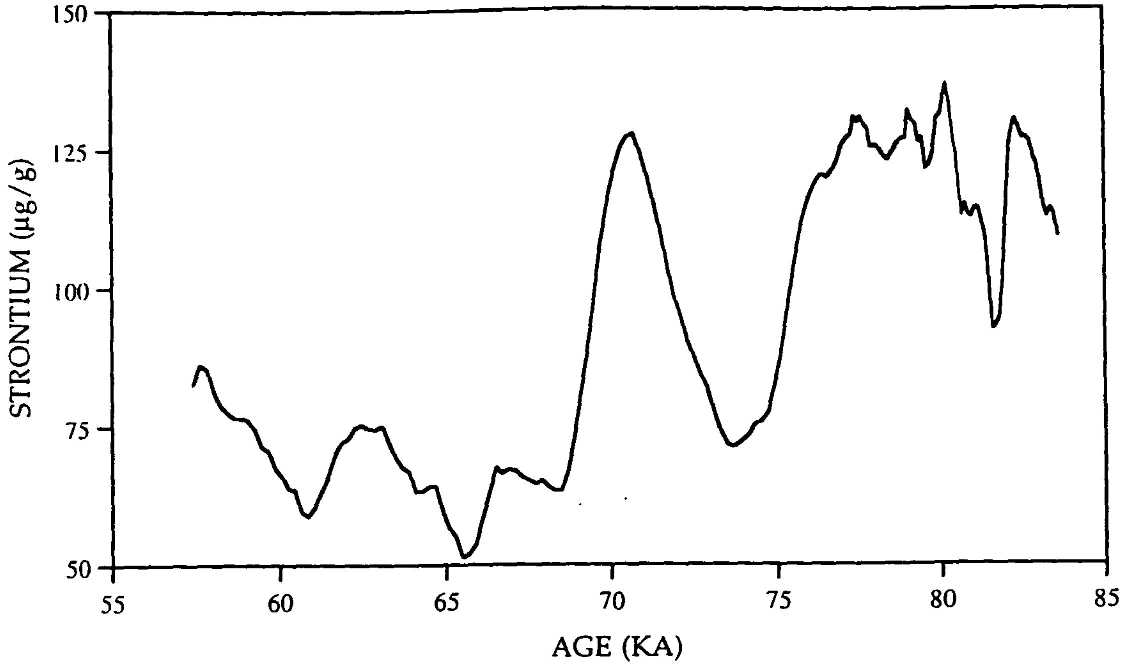

Figure 5 - Five-point running means of temporal variations in strontium content determined for 5 mm intervals along the longitudinal axis of the stalagmite (after Goede, 1994).

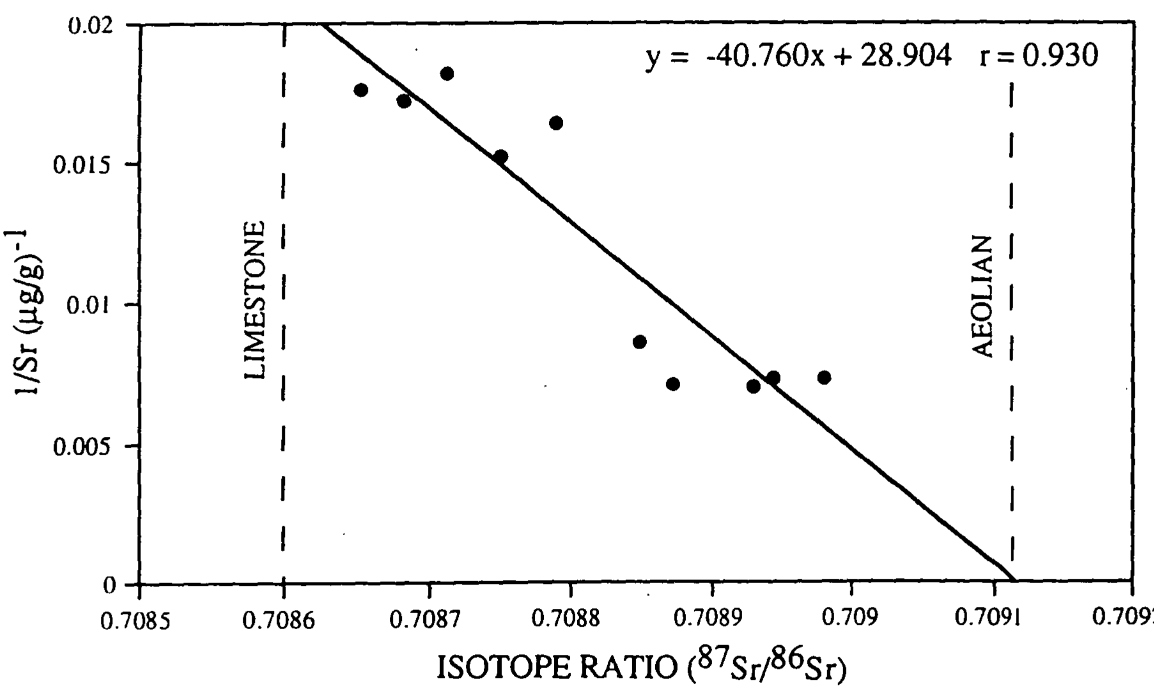

Figure 6 - Mixing diagram of strontium concentrations 1/Sr $(\mu g/g)^{-1}$ plotted against $^{87}Sr/^{86}Sr$ ratios shows a negative correlation between the two variables with the data falling into two distinct groups. Extrapolation of the relationship to 1/Sr = 0 indicates a strontium isotope ratio of ~ 0.7091 for the exogenic source. The strontium isotope ratio of the local limestone is represented by a value of 0.7086.

based on interpolation and extrapolation of the FT3 and FT5 ages with the value for FT2 falling close to the line. It yields a growth rate of ~25 mm/ka from 76.2 to 56.5 ka. Thus the growth rate has clearly declined over time probably reflecting the progessively cooler climate, at least until 64 ka. More MS age determinations would be required to model the changing growth rate more closely.

4. Discussion

The results of strontium isotope analysis are shown in Table 2. The two limestone samples were collected from the immediate vicinity of the FT stalagmite and supply an isotopic signature for the limestone ($\Delta^{87}Sr = 0.70860 \pm 2$) that provides a local source of strontium for the speleothem. The ten speleothem samples were selected so that five came from the lower mode and five from the upper mode of strontium concentrations. The speleothem samples all have isotopic values higher than that of the limestone. In Figure 6 strontium concentrations (Sr) are plotted as 1/Sr in mg/g-1 against $^{87}Sr/^{86}Sr$ ratios showing the data falling into two distinct groups. The low strontium group shows an average $\Delta^{87}Sr$ value of 0.70872 while the high strontium group has an average $\Delta^{87}Sr$ value of 0.70892. The results provide clear evidence of a highly variable supply of strontium derived from a source external to the limestone bedrock. The $^{87}Sr/^{86}Sr$ ratio of this source is estimated from Figure 6 when 1/Sr = 0. A value of 0.7091 is obtained which is indistinguishable from the isotopic ratio of 0.70906 ± 0.00033 for modern seawater.

Assuming that the Sr isotopic variations are a result of a two component mixing between Sr derived from the limestone (0.70860) and seawater (0.70913) then from the relationship established in Figure 6 the relative proportions from each source can be calculated. For the lowest $^{87}Sr/^{86}Sr$ sample with a ratio of 0.70865, this corresponds to ~10 % of Sr from seawater and for the high $^{87}Sr/^{86}Sr$ sample with a ratio of 0.70895 this corresponds to ~70 % from seawater. These however require relatively high proportions of marine aerosol input which is inconsistent with other trace element evidence discussed below.

Table 2 - Strontium isotope analysis of two limestone (LI) and ten stalagmite (FT) samples.

Sample no.	Strontium (µg/g)	$^{87}Sr/^{86}Sr$
LI3	n. d.	0.70860 ± 3
LI4	n. d.	0.70860 ± 2
FT45	137	0.70898 ± 1
FT75	142	0.70893 ± 2
FT165	136	0.70895 ± 2
FT220	116	0.70885 ± 2
FT300	140	0.70887 ± 1.5
FT590	58	0.70868 ± 1.8
FT615	61	0.70879 ± 2
FT640	57	0.70865 ± 2
FT660	66	0.70875 ± 1
FT755	55	0.70871 ± 2.4

Significance of strontium variations

The rapid transitions between the two modal concentrations of strontium indicated in figure 5 indicate the operation of what has been termed a switching mechanism. The pattern was first described from variations in electrical conductivity in the GISP2 Greenland ice core and was attributed to abrupt fluctuations in the concentration of atmospheric dust presumed to have been caused by rapidly changing directions of strong winds (Taylor et al, 1993).

An aeolian source of strontium may be derived either from seasalt aerosols or from terrestrial dust. A dust source from inland Australia as pointed out by Grousset et al. (1992) has a range of strontium isotope values from 0.7218 to 0.7634 based on five samples from Fowlers Gap and the Great Sandy Desert. Input from such high radiogenic sources is however not consistent with the strontium isotopic ratio versus 1/Sr correlation shown in figure 6. Therefore if the source is terrestrial in origin the obvious provenance would be calcareous sediment exposed on the continental shelf and in coastal dune areas of Bass Strait and perhaps of western Victoria and the southeast of South Australia with Sr compositions similar to modern seawater. Information on sealevels over the time period of speleothem formation can be estimated from a sealevel curve presented recently by Chappell (1996). It is based on recently redated coral terraces on the Huon Peninsula in Papua-New Guinea and on temperature corrected benthic oxygen isotope data from deep sea cores. It indicates that during the period of speleothem formation (84 - 56.5 ka) sealevels were at all times lower than today ranging from -20 metres at 80 ka to -80 metres at 65 ka.

A seasalt origin of strontium at our site appears unlikely for the following reasons:

(1) Even today the site is approximately 100 km inland from the west coast and separated from it by a series of north-south trending mountain ranges. During the period of speleothem deposition the sealevel would have been significantly lower than today and the distance from the coast correspondingly greater.

(2) Changes in strontium content between the two modal concentrations are abrupt whereas substantial sealevel changes by their very nature would have to

take place over a period of thousands of years.

(3) Seasalt is rich in bromine and Goede and Vogel (1991) have shown that bromine, like strontium, is readily incorporated in significant quantities in speleothems from caves in coastal areas. Twenty samples spaced at 40 mm intervals along the length of the FT core were analysed for bromine by NAA (nuclear activation analysis) with values ranging from 0.5 to 3.9 µg/g. If the bromine and strontium had both been derived from seasalt, a significant correlation would have been expected between concentrations of the two elements. Correlation analysis failed to find such a relationship ($R^2 = +0.161$).

It appears likely therefore that continental dust blown from the continental shelf by strong winds is the source responsible for the highly variable addition of non-limestone strontium to the stalagmite during its period of growth. Much of the dust is likely to have been calcareous as there would have been a large source area of calcareous dune and shallow marine sediments in Bass Strait with more distant sources both along the coasts and on the shallow continental shelves of South Australia and Western Victoria. It appears likely that while lower sealevels provided a suitable source area, the amount of aeolian dust fallout at the site above the cave was controlled primarily by the direction of strong winds with strong north-westerly winds bringing much larger quantities than strong westerly winds (Figure 8).

There is no information on modern rates of dust fallout over Tasmania but elsewhere in southeastern Australia Tiller et al. (1987) quoted in Hesse (1994) report a dust accession rate near Adelaide during three non-drought years (1978-80) of 5 to 10 tonnes/km^2/year. Windom (1969) made an estimate of the dust accession rate to the Tasman Glacier in the New Zealand Alps of 1.2 tonnes/km^2/year based on the amount of dust, presumed to be of Australian origin, trapped in glacier ice. Modern interglacial conditions of air circulation may be as relevant to the period of record than glacial conditions because high strontium levels in the stalagmite tend to be associated with times of relatively mild temperature conditions (Figure 7).

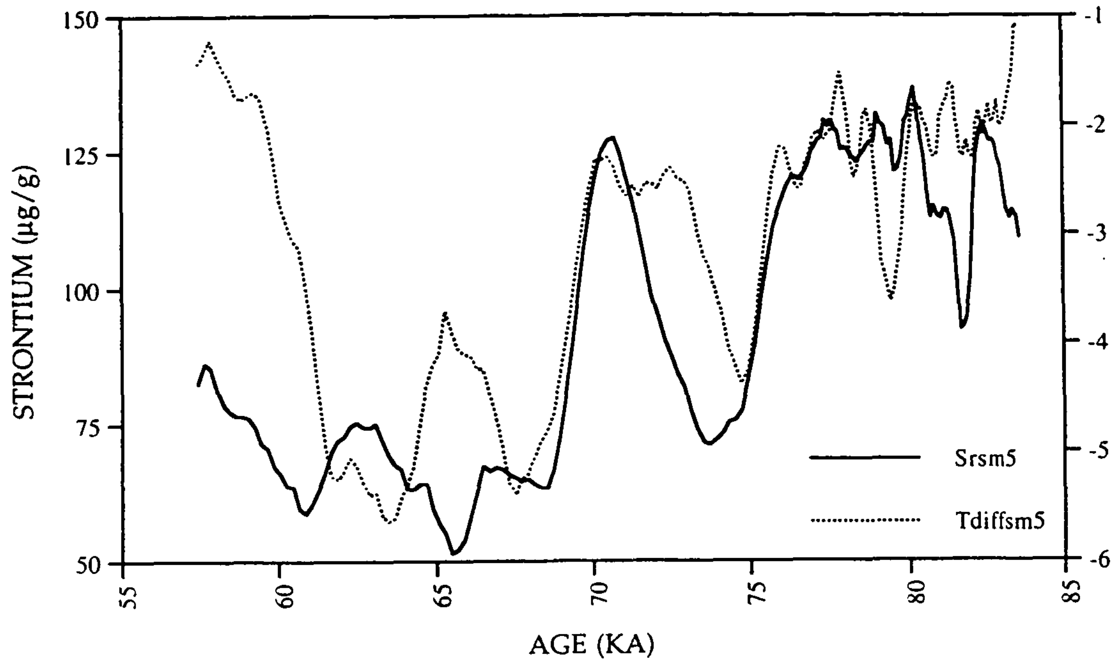

Figure 7 - Five-point running means of temporal variations in strontium content with superimposed estimates of temperature depression relative to today (8.3 °C) based on five-point running means of oxygen isotope values. They are calculated using a modern $d^{18}O$ value for calcite of -4.0 ‰ PDB and a reduction of 1 °C for every 0.26 ‰ lowering of the $d^{18}O$ value (Desmarchelier and Goede, 1996).

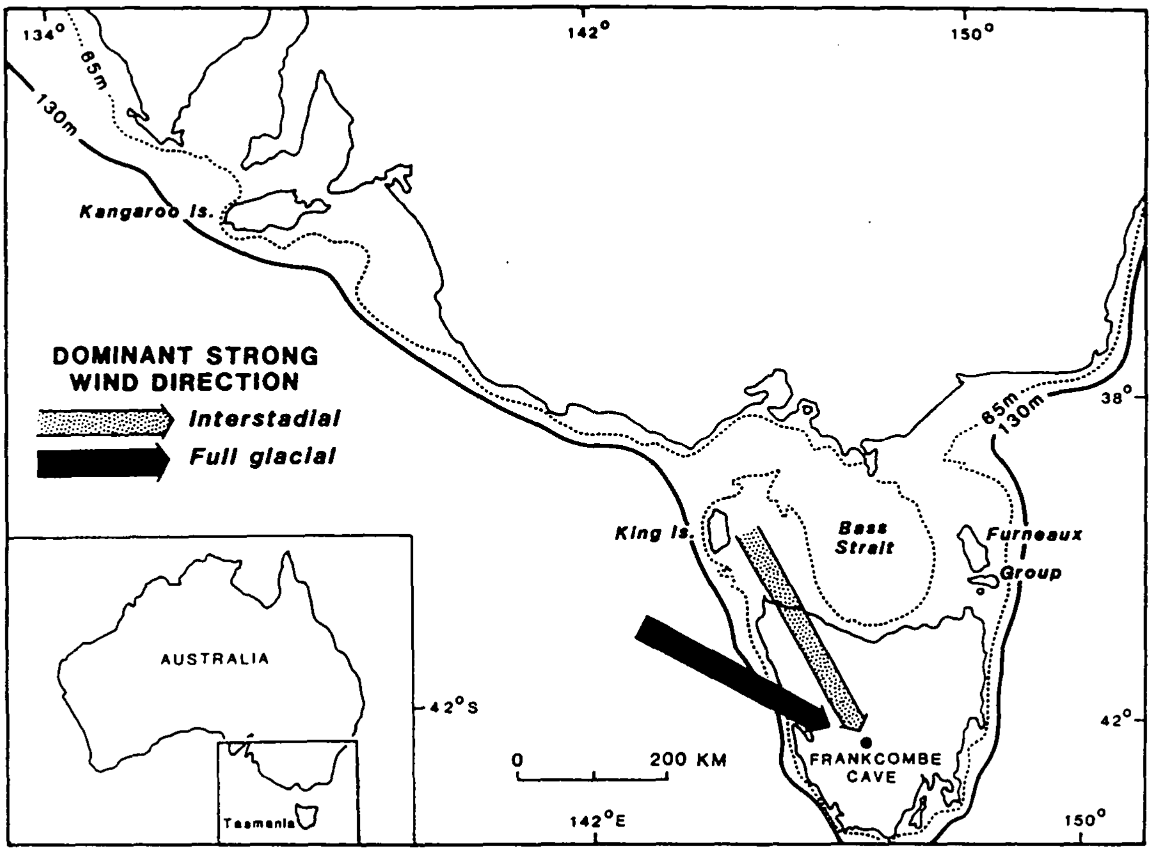

Figure 8 - Map of southeastern Australia and Tasmania showing the extent of the continental shelf with sealevels at -65 m and -130 m. During the growth period of the FT stalagmite sealevel varied from approximately -20 m to -80 m (Chappell, 1996). During interstadial periods dominant strong winds with a more northerly component are believed to have blown calcareous dust from the King Island region of what is now part of Bass Strait. Under full glacial conditions more westerly winds would have blown much smaller amounts of dust from the narrow continental shelf to the west of Tasmania with a possible long-distance dust component from the continental shelves of Western Victoria and S.E. South Australia. Information on bathymetry was obtained from Jones (1977) and Porch and Allen (1995).

During full glacial conditions the flux of aeolian dust would have been at a maximum as Hesse (1994) has demonstrated on the basis of evidence from his Tasman Sea cores. However, under full glacial conditions Tasmania appears to have experienced a pronounced zonal circulation pattern with the strongest winds coming from the west rather than the north-west.

Strontium content in stalagmites has been suggested as a possible palaeothermometer but not enough work has been done to verify this (Gascoyne, 1983, Goede and Vogel,1991). Goede (1994) showed a highly significant correlation between strontium content and oxygen isotope values (R^2 = 0.3697) in the FT stalagmite but did not regard it as evidence of temperature dependence because the larger concentrations of strontium were suspected to be predominantly of aeolian origin, a view that has been confirmed in this paper.

The relationship of strontium concentrations with oxygen isotope values (and therefore with palaeotemperatures) is now investigated further by separate correlation regression analyses of the low strontium (<100 μg/g) and high strontium (>100 μg/g) groups of samples by correlating each group with the corresponding oxygen isotope values (Figures 9 and 10). For the low strontium group there is a highly significant correlation between the two variables ($n = 79$, $r = 0.492$, $p < 0.001$), but for the high strontium group where most of the strontium has been shown to be of aeolian origin, the correlation is not statistically significant ($n=91$, $r = 0.194$, $p > 0.05$). It indicates that while there is a positive correlation between temperature and strontium derived predominantly from the limestone the temperature effect on strontium content is minor compared with that of aeolian accession.

5. Conclusions

Strontium isotope analysis has proved to be a useful tool in confirming that the bimodal distribution pattern of strontium content in the FT stalagmite was due predominantly to the highly variable addition of strontium from a non-limestone source, believed to be continental dust derived from exposed continental shelf areas to the north-west of the state. In south-central Tasmania at

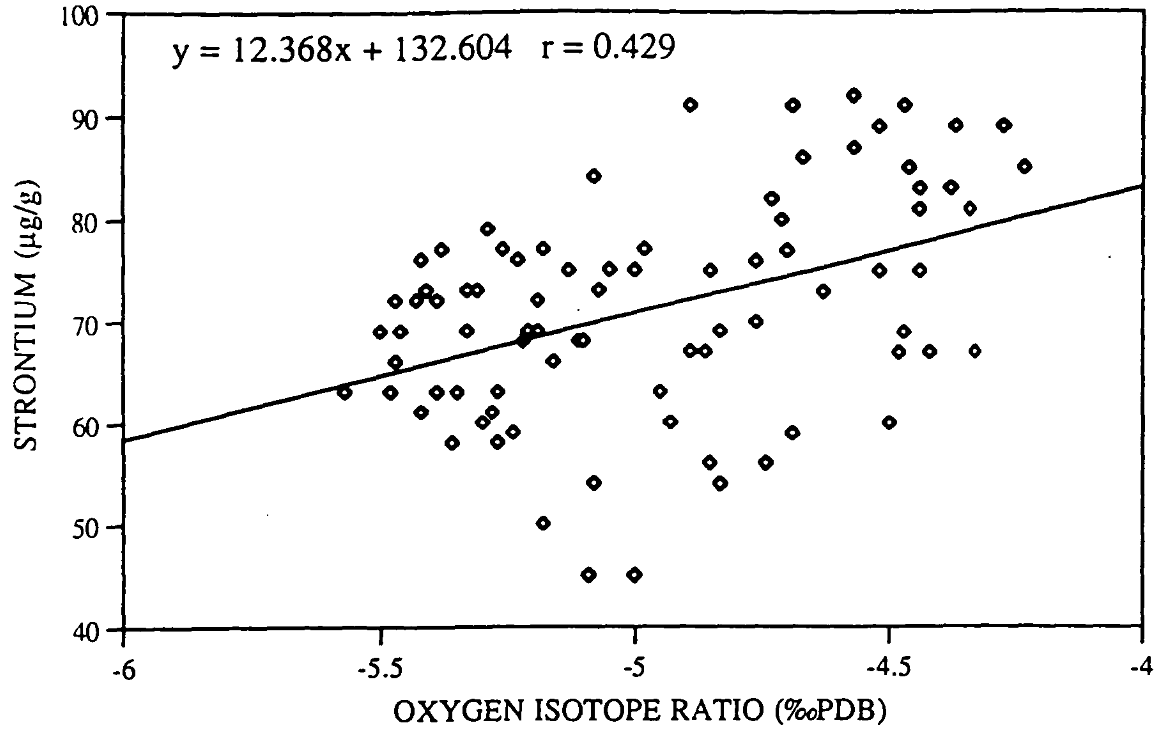

Figure 9 - Correlation regression analysis of low strontium samples (<100 mg/g) with oxygen isotope values.

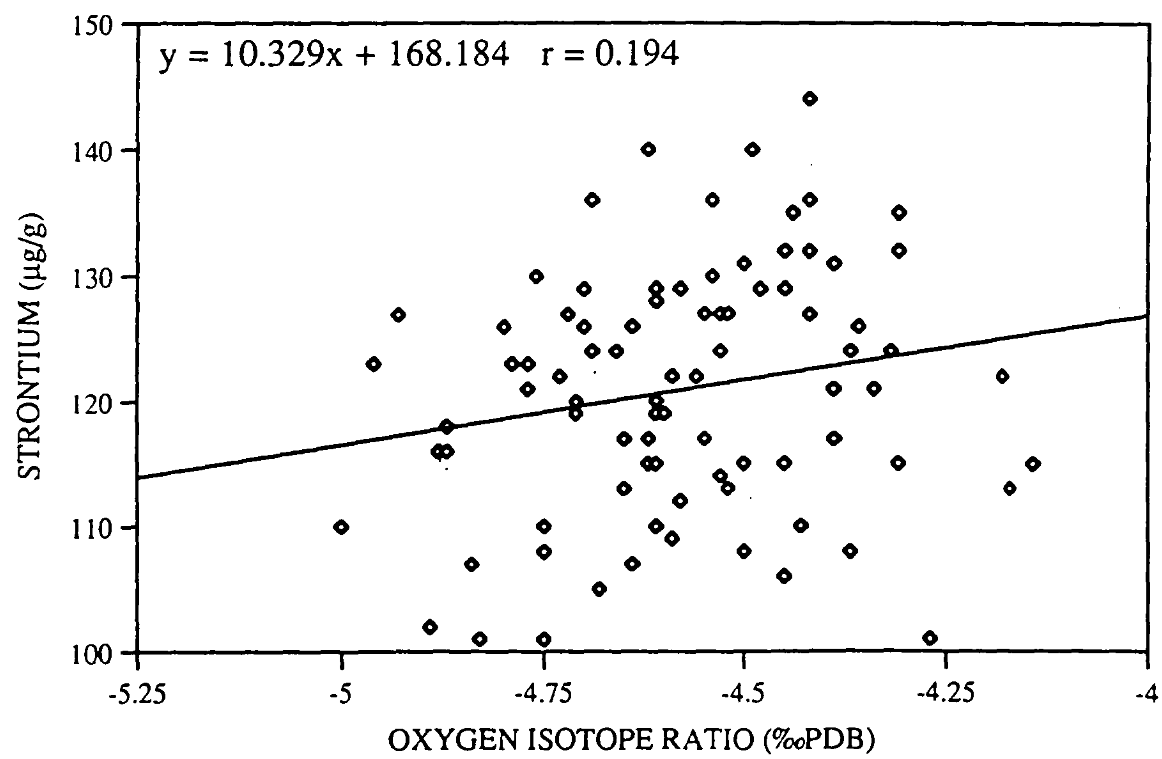

Figure 10 - Correlation regression analysis of high strontium samples (>100 mg/g) with oxygen isotope values.

least, the accession of dust appears to have been controlled by prevailing strong wind directions rather than by its rate of production on the Australian continent which on the evidence available (Williams et al. 1993) is likely to have been highest during glacial maxima.

When secular changes in strontium content of speleothems are studied in other parts of the world one would expect to find that in most cases they would be more directly related to the rate at which aeolian dust is being generated.

In near coastal areas, where seasalt provides a significant source of strontium, temporal variations of this element in speleothems may indicate the changing distance of the site from the coast with changing Quaternary sealevels.

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